

U.S. Geological Survey Program on the South Florida Ecosystem

Proceedings of South Florida Restoration Science
Forum, May 17-19, 1999, Boca Raton, Florida

For participating USGS projects

U.S. GEOLOGICAL SURVEY
Open-File Report 99-181



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By Sarah Gerould and Aaron Higer, Compilers

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Executive Summary

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INTRODUCTION

As land and resource managers see the value of their resources diminish, and the public watches the environments they knew as children become degraded, there are increasing calls to restore what has been lost, or to build productive ecosystems that will be healthy and sustainable under the conditions of human use. The U.S. Geological Survey's (USGS) Placed-Based Studies Program was established to provide sound science for resource managers in critical ecosystems such as South Florida (fig. 1). The program, which began in south Florida in 1995, provides relevant information, high-quality data, and models to support decisions for ecosystem restoration and management. The program applies multi- and interdisciplinary science to address regional and subregional environmental resources issues.

ENVIRONMENTAL RESTORATION: A PARTNERSHIP

A consensus has emerged among Federal and State agencies and environmental groups that south Florida and the Everglades (fig. 1) ecosystem should be restored as much as possible to its original condition. Following the settlement of a lawsuit on Everglades water quality, a Federal task force, chaired by the Department of the Interior (DOI), was formed in 1993 to oversee restoration efforts (fig. 2). The task force was enlarged in 1995 to include 25 representatives of Federal and State agencies and Indian tribes. A Science Coordination Team (SCT), consisting of representatives of these agencies

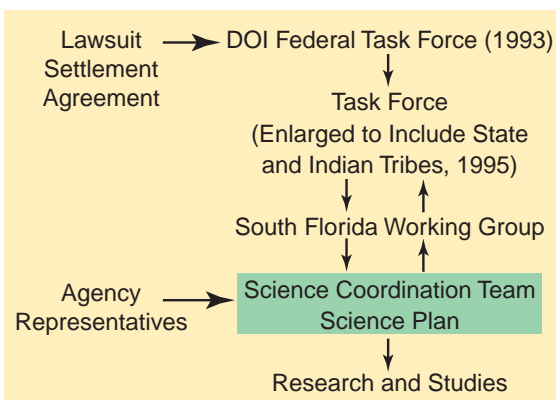


Figure 2. Diagram of science development for the restoration of south Florida.



Figure 1. Satellite image of south Florida showing boundary of the South Florida Ecosystem Program.

and tribes, advises the task force (fig. 2) on scientific investigations needed to support restoration. These investigations include characterizing and comparing the predrainage system with the present system, determining key characteristics of the predevelopment ecosystem, providing natural science input to and assessment of the redesign of

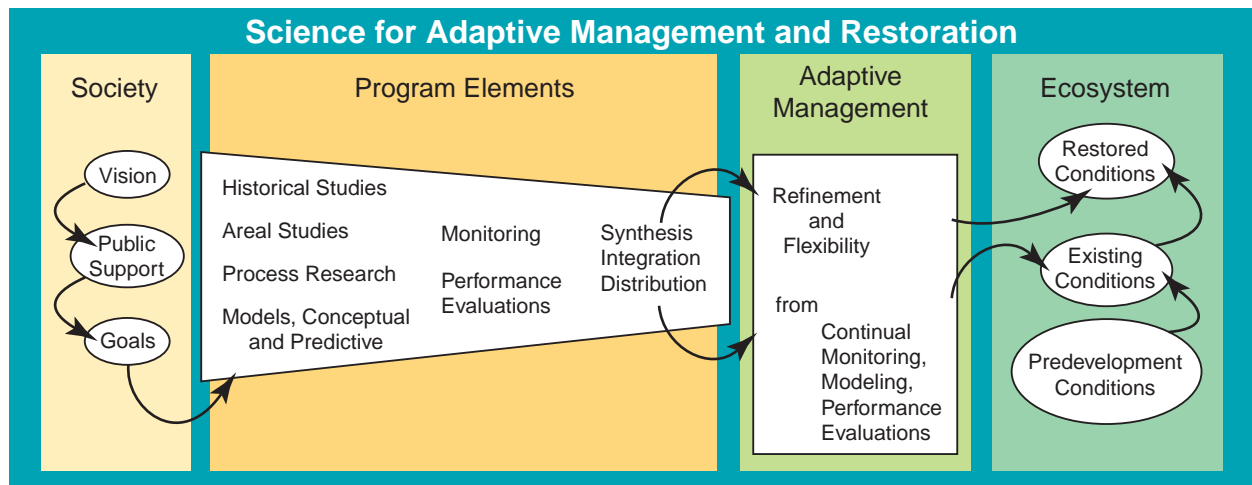


Figure 3. Diagram of science for adaptive management and restoration in south Florida.

structures and operations of the Central and Southern Florida Project Comprehensive Review Study (the Restudy), assessing the hydrologic and ecological results of the Restudy modifications through pre- and postmodification monitoring and modeling, modifying the design of the modifications to make improvements based on monitoring and modeling results, and characterizing the potential effect of the project on mercury accumulation. Many of the scientific activities are carried out by the USGS, which is the principal science agency of the DOI. The USGS works and collaborates with researchers in academia, State Government, and elsewhere in the Federal Government to bring the right mix of expertise needed for the scientific task.

SOUTH FLORIDA ECOSYSTEM PROGRAM

The South Florida Ecosystem Program is one of the Nation's Placed-Based Studies. The program began with a diverse body of projects encompassing cartographic, geologic, and hydrologic disciplines, and was guided from the start by scientific demands of ecosystem restoration. Projects have been selected based on the ranking of proposals by agencies involved in restoration, or based on the results of scientific review processes which highlighted additional scientific needs. Recently, the SCT has assumed the major responsibility for coordinating and selecting scientific studies needed for restoration.

An important part of the program is the facilitation of scientific linkages between disciplines. The multi- and interdisciplinary approach brings together scientists from appropriate operational units to apply their diverse expertise to common problems. Information from one discipline is designed to be used by scientific colleagues in other disciplines. When the National Biological Survey joined the USGS and became the Biological Resources Division in 1997, the USGS was able to provide a more integrated and comprehensive scientific service for land and resource managers.

Many studies in the program are nearing completion. As studies are completed, emphasis is shifting to completing research reports, archiving data from the ongoing projects, and preparing topical synthesis documents. Synthesis documents will summarize and integrate USGS accomplishments and understanding to date, as well as describe the relevance of the program's research to management issues. Synthesis will also identify unanswered questions and make recommendations for continuing research directions.

Program Elements

The program in south Florida has several broad work elements that contribute to science for adaptive management and restoration (fig. 3). The elements include:

- **Historical Studies of the Ecosystem**—The objective of historical studies is to better define recent (last few hundred years) climatic and environmental conditions in south Florida. Techniques include review of historical records and analysis of sediment cores by using charcoal, pollen, spores, and invertebrate skeletons as indicators of past environments. Results from these studies help managers define goals for restoration based on predevelopment conditions.
- **Areal/Site Studies**—Multidisciplinary studies, which are confined to specific areas or sites such as Florida Bay, Biscayne Bay, and the southern inland coastal systems in southern and eastern Dade County, provide biologic, cartographic, geologic, and hydrologic information that focuses on the needs associated with restoration activities.
- **Geochemical Process Research**—Research on the biological and chemical processes that affect and control the cycling of nutrients, sulfur, mercury, and other contaminants improves understanding of the south Florida ecosystem and its response to restoration activities.
- **Model Development**—Robust models of ecological processes and the hydrologic system provide predictive capabilities for managers of the ecosystem and improve understanding of probable ecosystem responses to restoration activities. Development and applications of models of sheetflow, ground-water movement, evapotranspiration in different vegetative communities, and ecological interactions are all underway.
- **Data Synthesis and Information Dissemination**—Topical syntheses will analyze, summarize, and integrate USGS research and understanding, and describe the relevance of this research to management issues. Synthesis is also planned at the interagency level, incorporating multidisciplinary information collected by all agencies involved in south Florida restoration. The USGS World Wide Web site, <http://sflwww.er.usgs.gov> (fig. 5) allows easy access to program information by the public, interested scientists, and resource managers. The web site includes access to scientific data and metadata, information on current projects and investigators, and reports.

PREDEVELOPMENT IN SOUTH FLORIDA

At the time of settlement by Europeans (mid-1800's), south Florida was a lush, subtropical wilderness. The Everglades was part of a larger watershed: the Kissimmee-Okeechobee-Everglades that extended for more than half the length of the Florida Peninsula and encompassed one of the largest wetlands in the continental United States. These wetlands and the entire watershed (fig. 4) provided the freshwater that sustained the high productivity and abundant fisheries of coastal waters.

The wetlands of south Florida were regarded as being inhospitable and without intrinsic value. In the early 1900's, draining the wetlands was considered to be essential for commerce and safety. Loss of lives as a result of hurricane flooding in the 1930's accelerated drainage projects, primarily in the Everglades. Drainage has resulted in the construction of more than 1,400 miles of primary canals and more than 100 water-control structures.

SOUTH FLORIDA TODAY

South Florida includes urban areas near the coast, intensively developed agricultural areas in the northern Everglades, rangelands, and wetlands. The southern part of the ecosystem is mostly under public ownership or control as parks, preserves, sanctuaries, conservation areas, and refuges (see fig. 4).

Three major interests compete for water: urban, agriculture, and the natural ecosystem. The rapidly growing urban population along the coast requires a steady water supply and flood protection. Agricultural lands around Lake Okeechobee and near the southeastern Everglades need flood protection and seasonal water availability, and are a source of nutrients to areas downstream. The natural ecosystem requires water low in nutrients, seasonal wet and dry periods, and occasional periods of flooding and drought. Accommodating all three interests is a challenge for water managers.

TODAY'S ISSUES

Drainage and development have contributed to a number of environmental problems. These include loss of soil, nutrient enrichment, contamination by pesticides, mercury buildup in the biota, fragmentation of landscape, loss of wetlands and wetland functions, widespread invasion by exotic species, increasingly frequent algal blooms in coastal waters, seagrass die-off, and declines in fishing resources. Changes in the hydrologic system are thought by many to be the root cause of the dramatic declines in fish and wildlife populations and habitat alteration across the south Florida ecosystem.

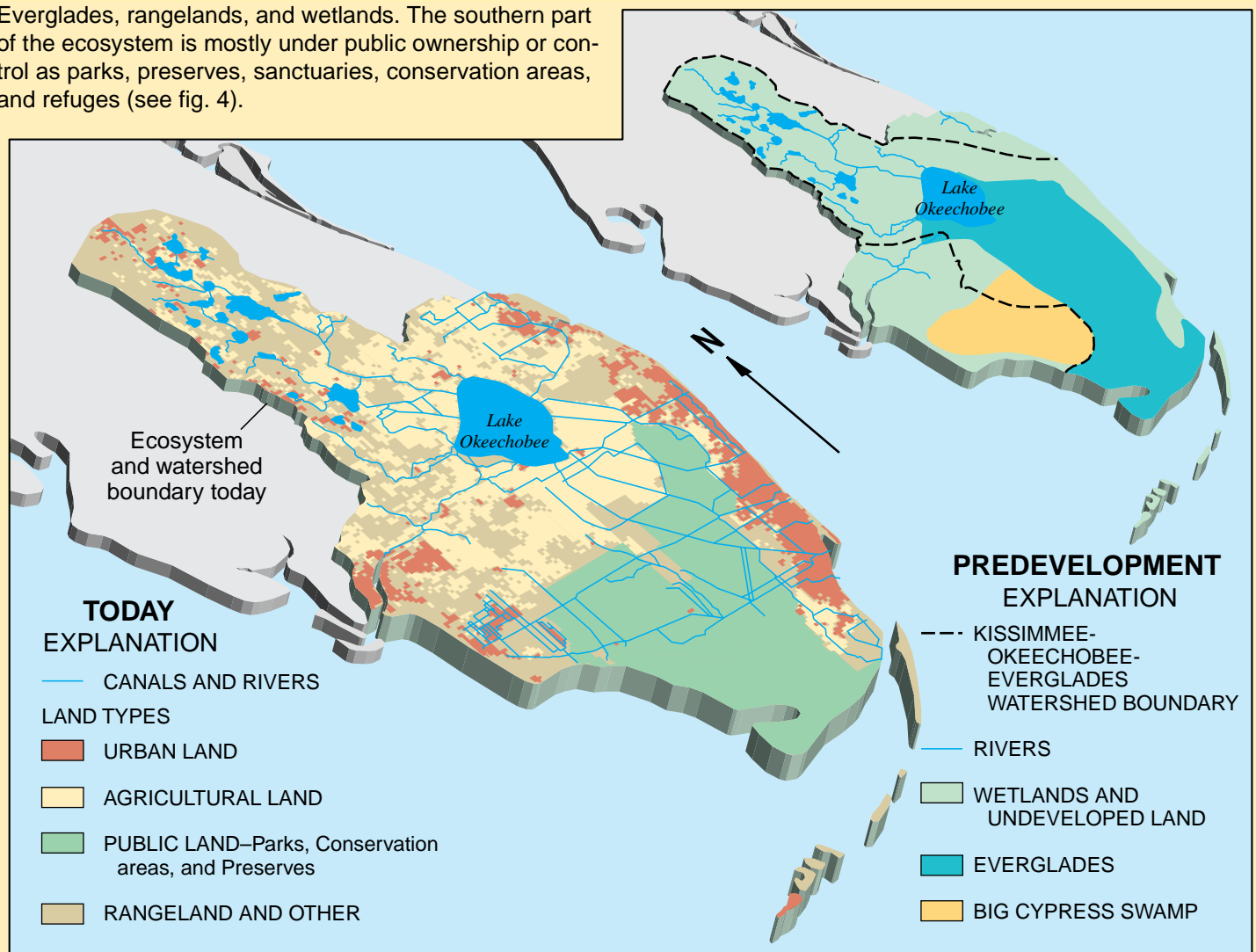


Figure 4. Changes in land cover and drainage in south Florida—predevelopment and today.

Program Results that Contribute to Management

Results from the program are already contributing to restoration management. Some examples include:

- Providing agencies with essential cartographic and hydrologic data needed to model timing and pattern of flows, and helping to evaluate these models, such as the South Florida Water Management District's Natural Systems Model used in planning restoration.
- Developing models that are essential for restoration, such as the Across-Trophic Level System Simulation (ATLAS) model that was recently used by managers to adjust water flows to protect habitat for the Cape Sable seaside sparrow.
- Providing information on historical conditions that place current conditions in perspective. For example, USGS research has shown that the marshes of the central Everglades have been drier this last century than in the last 2,000 years, that salinities in

Florida Bay and Biscayne Bay have been increasing over the last 100 years, and that fresh and brackish-water biota have been replaced by seagrasses in some nearshore bay locations. Restoration will require redirection of freshwater to historical pathways to reverse recent trends.

- Identifying a potential pathway for nutrients from wastewater disposal wells on the Florida Keys to enter marine waters by eastward ground-water flow under the Keys and by upward seepage into surface waters.
- Confirming that some of the phosphorus inputs to the Everglades originate from fertilizers and contribute to over-enrichment, degraded water quality, and biological alterations.
- Showing that sulfur inputs to the Everglades play a major role in mercury methylation, can alter microbial cycles, and produce toxic hydrogen sulfide.

—By Benjamin F. McPherson, Sarah Gerould, and Aaron Higer

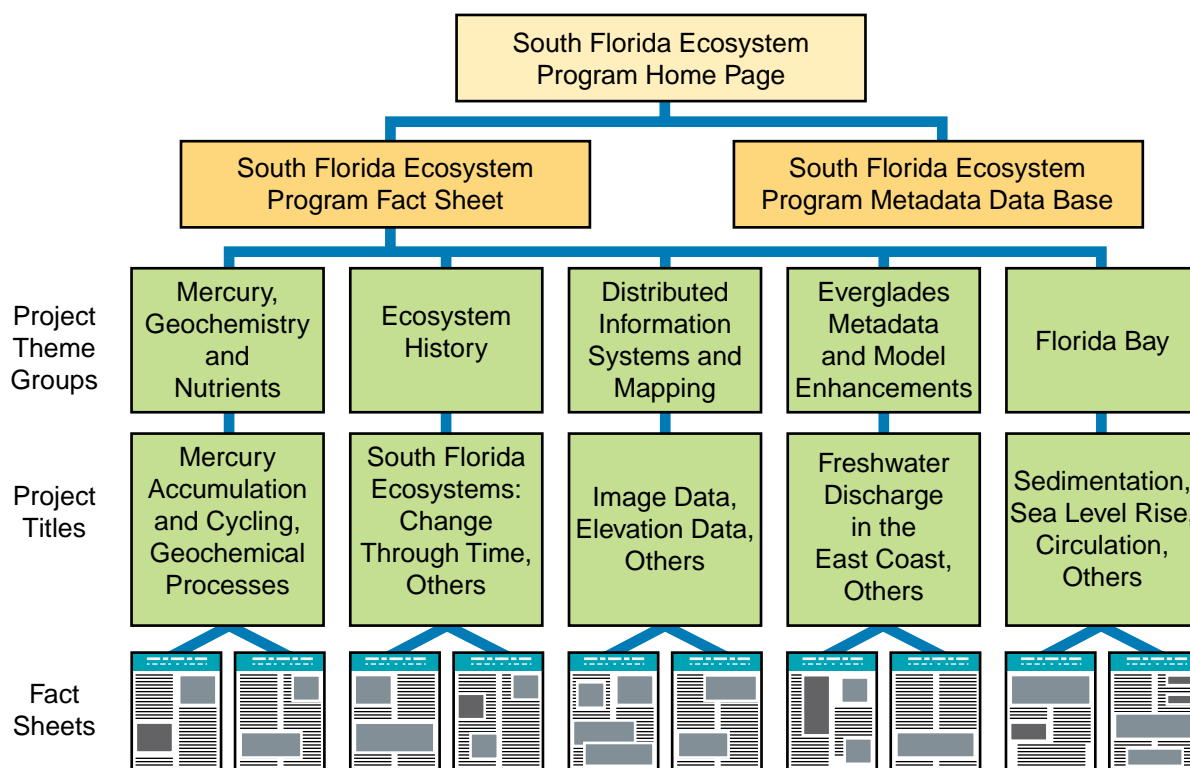


Figure 5. Organization of the South Florida Ecosystem Program web site, data base and fact sheets.

FUTURE DIRECTIONS

The USGS South Florida Ecosystem Program will emphasize data and information dissemination and synthesis in coming years. Results from the program will provide technical information needed to measure and assess restoration success and sustainability in south Florida.

Collaborators

- Bureau of Indian Affairs
- Florida Department of Environmental Protection

- Florida Geological Survey
- Florida Institute of Oceanography
- National Marine Fisheries
- National Marine Sanctuary
- National Park Service
- National Resource Conservation Service
- Office of the Governor
- South Florida Water Management District
- U.S. Army Corps of Engineers
- U.S. Environmental Protection Agency
- U.S. Department of Justice
- U.S. Department of Transportation
- U.S. Fish and Wildlife Service

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SOUTH FLORIDA ECOSYSTEM RESTORATION SCIENCE FORUM

***May 17-19, 1999
Boca Raton, Florida***

The purpose of the Forum is to highlight the powerful connection between science and management decisions in restoration efforts. The public's investment in science is paying off in support of better management decisions and restoration of imperiled south Florida Ecosystems, including the internationally recognized, globally significant Everglades. The Forum affords a unique opportunity for elected officials and other policy- and decision-makers, along with the general public, to see—under one roof—highlights of the most significant restoration science and management efforts underway.

The Forum promotes the link between science and management. Scientists and decision-makers will come together to discuss the needs of each in order to ensure that plans for restoration are based in science and are the most cost-effective and highest quality possible. Continued vigilance over south Florida ecosystems is essential to prevent further harm and to restore them.

Representatives from numerous federal, state, local, and non-governmental entities are organizing the Forum for the Science Coordination Team of the South Florida Ecosystem Working Group. The U.S. Geological Survey and the south Florida Water Management District are the primary hosts of the Forum.

Origins, Residence Times, and Nutrient Sources of Marine Ground Water Beneath the Florida Keys and Nearby Offshore Areas

By J.K. Böhlke¹, L.N. Plummer¹, E. Busenberg¹, T.B. Coplen¹, E.A. Shinn², P. Schlosser³

Ground water is a potential source, sink, and carrier of nutrients and other contaminants beneath the Florida Keys and nearby offshore regions. Ground-water flow patterns and nutrient sources need to be understood to assess and predict the dispersal of anthropogenic contaminants such as injected wastewater. Small-scale tracer studies indicate rapid local lateral movement of ground water near the Keys, and water-level monitoring studies indicate hydraulic potentials for ground-water flow. Those results, however, do not address directly the large-scale extent of ground-water transport and the origin of nutrients observed in offshore ground water. A variety of environmental isotopes and geochemical tracers are being used to provide information on the sources, flow directions, exchange rates, and chemical characteristics of ground water underlying the region at depths of about 3 to 20 m below the sediment surface. In this study a multi-tracer approach was used to address a variety of scientific problems: (1) salinity data combined with stable H and O isotopes of water provide information about ground-water sources; (2) CFC's, ^3H , and He isotopes provide information about the subsurface residence times of ground water; and (3) ^{14}C and stable isotopes of C-, N-, and S-bearing constituents provide information about sources of solutes, and chemical reactions among ground water, nutrients, and aquifer materials. Two major offshore sampling surveys were completed in 1996 and 1997, and additional samples were obtained from wells on land in 1998. In total, these constitute a set of representative samples of surface water and ground water from a large part of Florida Bay, the Keys, and offshore areas extending to the reef tract in the south.

Stable H- and O-isotope ratios and salinities indicate at least four mixing components: seawater, meteoric water, evaporated seawater, and evaporated meteoric water. Isotopic data for tap water, wastewater, and injected wastewater were consistent with a common freshwater source on the Florida mainland, and with mixing of wastewater and bay-type marine ground water in the subsurface near wastewater injection sites. Atlantic Ocean side ground water had values of $\delta^2\text{H}$ ($+10 \pm 2 \text{ ‰}$), $\delta^{18}\text{O}$ ($+1.15 \pm 0.15 \text{ ‰}$), and salinity ($35 \pm 1 \text{ ‰}$) that generally were equal to those of offshore seawater. Those results are consistent with Atlantic Ocean side ground water having originated from recharge of normal seawater. Bay-side ground water generally had higher values of $\delta^2\text{H}$ ($+13$ to $+20 \text{ ‰}$), $\delta^{18}\text{O}$ ($+1.5$ to $+2.7 \text{ ‰}$), and salinity (35 - 39 ‰) compared to offshore seawater, with the highest values occurring in the eastern part of the bay and more marine values toward the west. The regional patterns of H and O isotope variations in bay-side ground water are similar to the patterns in bay-side surface water. Those results are consistent with the bay-side ground water having originated from recharge of evaporated bay water during times of high bay salinity, and they indicate little regional-scale lateral ground-water transport beneath the bay. Ground-water samples from beneath the Keys and from short distances (less than a few hundred meters) offshore to the south had isotopic compositions consistent with transport of bay water toward the ocean side in the subsurface. However, the salinity and isotope results so far have not supported long-distance transport (more than a few hundred meters) of bay-derived ground water to sites far offshore on the Atlantic Ocean side (for example, to the reef) within the depth range investigated.

Concentrations of CFC-12 in marine ground water on both sides of the Keys were consistent with atmospheric equilibration and subsequent isolation (recharge) at times ranging from 0 to more than 50 years ago. Degradation may have altered significantly the concentrations of CFC-11 and CFC-113 in most samples. Minor CFC contamination was detected in water from a canal on Key Largo and

in wastewater at the Keys Marine Laboratory, but it did not appear to be widespread. Apparent recharge ages derived from analyses of ^3H and He isotopes ranged from 0 to more than 30 years, and reconstructed values of initial ^3H were in the range of 0-10 TU. ^3H - ^3He ages and CFC-12 ages were generally correlated, but the CFC-12 ages commonly were on the order of 10-50 percent older than those ages based on ^3H - ^3He . Apparent ages derived from both CFC and ^3H - ^3He methods were stratified. Wherever more than one depth could be sampled at the same site, the deeper water appeared to be older. Estimated concentrations of non-atmospheric radiogenic ^4He were on the order of 0.1×10^{-8} ccSTP/g (cc at Standard Temperature and Pressure/g). The $\delta^{13}\text{C}$ values of dissolved inorganic carbon (DIC) indicate varying contributions from both organic carbon oxidation and carbonate mineral recrystallization. Un-normalized ^{14}C abundances in DIC (mainly bicarbonate) range from less than 10 percent to about 115 percent "modern," consistent with a large range of apparent radiocarbon ages. Much of the variation in apparent ages, however, can be accounted for by chemical reactions between seawater with high ^{14}C and carbonate sediments with low ^{14}C . Combined results of chronologic tracers indicate that the time scales of ground-water/surface-water exchange are on the order of years to decades at depths up to about 20 m below the sediment-water interface. Within those time scales, ground-water compositions are altered significantly by ground-water-aquifer interactions that may include release or consumption of nutrients.

Nutrient analyses confirmed that anoxic marine ground water throughout the area contained significant amounts of ammonium (10-80 μM). Concentrations of sulfide, methane, and bicarbonate also were elevated in the reduced water samples. The $\delta^{15}\text{N}$ values of ammonium in ground water near a site where treated sewage effluent is injected to the ground-water system were high (+9 to +12 ‰) and could be consistent with a wastewater source. The $\delta^{15}\text{N}$ values of ammonium in all other ground water were low, but variable (+3 to +8 ‰). There was not a strong correlation between ammonium concentrations and $\delta^{15}\text{N}$ values. It is possible that much of the ground-water ammonium was produced naturally by anaerobic degradation of N-bearing organic matter in sediments. Nitrate concentrations in most samples were low (< 1 μM). Nitrate concentrations greater than 5 μM were detected in wastewater and in ground-water samples that contained low-salinity components either from wastewater or from precipitation recharge. The highest nitrate concentrations were measured in treated wastewater and in shallow mixtures of wastewater and saline ground water. A minor source of N also was identified in the Keys water supply. Concentrations and isotopic compositions of dissolved nitrogen gas in most ground water were generally consistent with atmospheric equilibration between 20 and 28 °C before recharge. There was evidence in some samples for small quantities of excess N_2 that may have been derived from denitrification (reduction of nitrate to N_2). Excess N_2 in wastewater and in mixtures of ground water and wastewater near an injection site was apparently the result of denitrification of nitrate in the wastewater.

This project is providing quantitative information about the origins, residence times, and nutrient characteristics of marine ground water beneath the Florida Keys and nearby offshore areas. Chronologic and isotopic data for ground water are useful in assessing the extent and rate of movement of potential contamination in the subsurface. Nutrient chemistry and isotopic data are useful in distinguishing natural and anthropogenic sources of chemical constituents in ground water. These data and interpretations aid decision-making about wastewater treatment and disposal in the region. In addition, the study includes testing some new combinations of methods and sample types that could expand the list of approaches available to the scientific community for future investigations of similar problems.

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Historical Patterns of Change in the Florida Bay Ecosystem

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A critical component of any restoration effort is to establish the natural spatial and temporal variability that exists within the ecosystem. The U.S. Geological Survey Ecosystem History of Florida Bay Project has analyzed seven cores from four sites in Florida Bay in order to establish the patterns of variability within the ecosystem. The goals of this project are to determine (1) what the ecosystem was like prior to human intervention; (2) what is the natural range of variation within the system; and (3) whether recent changes in the system can be correlated to human factors, to natural events, or to a combination of factors.

Modern samples collected at 26 monitoring sites in Florida Bay provide the necessary proxy data for interpreting the downcore historical record. The physical parameters of the environment (including salinity, temperature, substrate, clarity) and the fauna (benthic foraminifers, ostracodes, and molluscs) and flora (palynomorphs and diatoms) present at each site are recorded. (Data from the modern samples and the cores are available at <http://geology.er.usgs.gov/gmapeast/fla/home.html>.) The environmental parameters controlling the spatial and temporal distribution of the biota are inferred from analysis of these modern samples. This information is extrapolated to downcore interpretations based on the biota present in the core.

Analyses of four cores located in the northern transitional, eastern, and central portions of Florida Bay reveal historical patterns of change in salinity and seagrass distribution. Changes in environmental parameters prior to 1900 are illustrated by the distribution of benthic fauna in two of the cores from central and eastern Florida Bay. Natural fluctuations occurred in salinity, but the amplitude of those fluctuations was limited to a 15 to 20 percent shift about the mean. Subtle changes occurred in the benthic fauna around 1910, but beginning around 1940, the pattern of salinity fluctuation departed substantially from the pre-1900 pattern. Post-1940, the salinity oscillates 40 to 60 percent about the mean. This pattern is seen in all indicators measured. Around 1970, a significant but short term decline occurred in salinity. A core from the northern transitional zone reflects changes in freshwater flow that have occurred during this century. The upper part of the core records a significant increase in salinity, with a slight decrease occurring in recent years. An eastern Florida Bay core represents an area of very high sedimentation rates; an increase in salinity occurs in the upper part of the core.

Changes in the interpreted salinity patterns around 1900 are consistent with the timing of the construction of the Flagler Railroad from 1905 to 1912, and the Tamiami Trail and the canal and levee systems between 1915 and 1928. Beginning around 1940, the changes in the frequency and amplitude of salinity fluctuations may be related to changes in water management practices, meteorological events (frequent hurricanes coupled with severe droughts in 1943 and 1944), or a combination of factors. These data suggest that the timing and delivery of freshwater into the Florida Bay system, and the circulation of waters in the system, whether due to human or natural factors, have changed significantly over the last two centuries, and restoration goals need to address these issues.

Natural fluctuations in the distribution of seagrass (predominantly *Thalassia*) are inferred from the shifts in relative abundance of epiphytal species preserved in the cores. All the cores show an increase in epiphytes and, therefore, in seagrass during the 20th century. An increase also occurs in epiphytal species that can dwell on macro-algal mats associated with *Thalassia* beds, which suggests

that an increase in algal-mats has occurred during the 20th century. The core from central Florida Bay records an extensive period during the 1800's of little to no vegetative cover of the substrate based on the near absence of epiphytic species in that segment of the core. Following this period, the epiphytic species increase rapidly in abundance, implying that vegetation has the ability to disseminate rapidly. These data are significant because they indicate that seagrasses fluctuate naturally over time, and that dense seagrass coverage is not necessarily the "natural state" for Florida Bay.

A preliminary analysis of the benthic foraminifers and molluscs taken from three replicate cores at the central and eastern sites has been completed, and the salinity and seagrass patterns seen in these cores are consistent with the data from the previous analyses, indicating that the data are representative of the conditions at those sites. Similar seagrass and salinity trends have been detected in Biscayne Bay (see Ishman and others, this volume), and corresponding changes have occurred in the terrestrial Everglades (see Willard and others, this volume). The correspondence of these changes throughout the ecosystem indicates that the agent of change is regional.

Understanding the natural spatial and temporal variability that exists within an ecosystem is a critical component of efforts to restore systems to their "natural state." The paleoecologic data preserved in undisturbed cores provide insight into past conditions, natural range of variability, and response of the system to change. This historical perspective on Florida Bay allows land managers to determine cause and effect relationships in the systems' responses to past changes. Additionally, the natural component of change can be filtered out of the human-induced component of change, thus allowing land managers to set realistic, cost effective, sustainable restoration goals. Goals contrary to natural patterns of change will be costly and may not be sustainable.

This work has involved collaboration and cooperation with a number of other agencies including Everglades National Park, South Florida Water Management District, National Oceanic and Atmospheric Administration, Florida Marine Research Institute, Keys Marine Laboratory, and Florida Geological Survey. We would like to thank our colleagues at those institutions for their assistance and cooperation in our research.

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Mangrove Forest Sediment Elevation Changes in Relation to Sea-Level Rise and the Florida Everglades Hydrological Restoration

By Donald R. Cahoon¹ and Thomas J. Smith III²

The mangrove forests of the southwest coast of Florida are a valuable coastal resource. Like most coastal ecosystems they provide important goods and services including fisheries production and shoreline stabilization (Costanza and others, 1997). The soils of the mangrove forest are deep peats (Gleason and Stone, 1994) produced by the below ground productivity of the mangrove trees themselves. Questions have arisen recently concerning the ability of mangrove ecosystems worldwide to keep pace with a rising sea level (Cahoon and Lynch, 1997). In southwest Florida the question is more complex because the effects of upstream hydrological modifications to the freshwater Everglades must also be considered. Added freshwater inflows to the mangrove zone may alter salinity and nutrient regimes which in turn may change the rate of peat accumulation.

Following Hurricane Andrew, in 1992, our research group began investigations into the hydrology and ecology of the mangrove forests of the southwest Florida coast including several State and federally protected areas: Everglades National Park, 10,000 Islands National Wildlife Refuge, and the Rookery Bay National Estuarine Research Reserve (Smith and others; Smith and Whelan; this volume). The present study is designed to take advantage of the network of permanent vegetation sampling plots and hydrological monitoring stations which are already in existence. It will add to the knowledge already being gained by providing key information on below-ground processes.

The study is establishing a network of Sediment Elevation Tables (SETs) to gain precise measurements (± 1 mm) of elevation changes over time (Cahoon and others, 1995; Cahoon and Lynch, 1997). The network will eventually encompass three river systems on the southwest coast of Everglades National Park: the Shark, Lostman's, and Chatham. On each river, sites will be established at the upstream freshwater marsh end; at a mid-river, marsh and mangrove area; and in a downstream river mouth location dominated by mangrove forest. These sites are being co-located with the South Florida Global Climate Change hydrology stations (see Smith and others, this volume). The method involves inserting an aluminum pipe as deeply into the sediment as possible, preferably to bedrock (7 meters in some parts of the study area). This provides a stable platform which does not move in relation to the elevation of the sediment. Measurements using the SET are then made from this platform. The initial set of SETs were installed at sites in the mid to lower Shark River and at Big Sable Creek in July 1998. Additional sites were added in the freshwater portion of Shark Slough and in the lower Lostman's River in January 1999. Initial readings were made in July 1998. Subsequent readings have been made in October 1998 and January 1999.

These readings bracket the passage of Hurricane Georges and Tropical Storm Mitch. Thus an added advantage is to examine periodic storm events on sediment elevation changes in the mangrove environment. Because of the preliminary nature of the data gathered to date, no analysis will be presented here. However, it is clear that as the network is developed, in conjunction with ongoing studies of vegetation and hydrology, we will be able to measure effects of the South Florida Ecosystem restoration as the hydrology of Shark River Slough is restored.

A significant part of the funding for this research was provided from the U.S. Department of Interior South Florida Ecosystem Restoration Program "Critical Ecosystem Studies Initiative" (administered through the National Park Service) and from the U.S. Geological Survey, Florida

Caribbean Science Center funds for the project “Disturbance Ecology of Tropical and Subtropical Mangrove Forested Wetland Communities.” Additionally, this project is a unique research task within the larger overall project “Vegetation Dynamics of the land-margin Ecosystems: The Mangroves of South Florida.”

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The Effects of Everglades Food Items (Prey) on Crocodilian Growth, Development, and Fertility

By P.T. Cardeilhac¹

This work is associated with the U.S. Geological Survey, Across Trophic Level System Simulation (ATLSS) Program and has the objective of supplying empirical information, particularly involving reproductive physiology, needed to develop a population model for the American alligator (*Alligator mississippiensis*). Nest monitoring at the Everglades National Park has shown that mean water levels in the park are closely correlated with nest production by the alligators. It is known that reproductive performance of the alligator is related to food quality and availability. However, the detailed effects of water levels on the availability of prey, their quality as a food item, the presence or absence of toxins or parasites, and the resulting effect on fertility are not known. Previous work on the alligator has shown that critical nutrients in the alligator diet affect health status, growth and specific reproductive parameters. Recently it has been shown that fatty acid profiles of fat in the diet affects egg fertility, embryonic survival, and possibly hatchling vigor. A knowledge of prey availability, quality and composition is necessary to predict its effect on health status, fertility, growth, and development in the alligator population of the Everglades. Consequently, knowledge of the effect of water levels and other environmental factors on prey availability and food value is necessary to predict its effects on health status, growth, development and reproductive performance. Thus, with appropriate data, the effects of water levels on nest-rate, clutch size, percent fertile eggs, embryo survival, hatch rate and hatchling vigor could be predicted by changes in types of prey available, quantities, quality and their potential for toxins and/or parasites. Quality or biological value of the dietary protein depends on its digestibility, amino acid profiles and sufficient energy for its utilization. Toxins and/or parasites in the prey can, of course, affect all parameters. Therefore, any predicted effect of nutrient status of the habitat should be confirmed by an evaluation of body condition, health status and breeding condition of the population. Body condition and health status of the alligator population are evaluated by measuring parameters such as death rates (size-gender-puberty profiles) physical condition, morphometrics, clinical values, pathology and microbiology. Breeding condition or reproductive potential of the population is evaluated by a determination of reproductive parameters such as percent adult females, sex ratio, nest rate, clutch size, egg quality, percent fertile (banded) eggs, embryo survival, hatch rate and hatchling vigor. These parameters are measured as quantitative evaluation-variables. This research offers methods to estimate these variables, accurately compare them with control samples, and provide a cost for each determination. The results provide the potential of allowing a more accurate prediction of the effects of water levels and other environmental factors on growth rate, development, and reproductive performance of the alligator.

Our initial studies on Everglades alligators have shown significant differences in size and shape of the eggs produced in the park and the hatchlings produced are significantly smaller than those from control areas. However, growth performance of the hatchlings does not appear to be significantly different from that of control animals. It has also been determined that body condition of the adults seems to be poor and clinical values of the animals indicates a chronic inflammation in at least some of the animals. These findings need to be confirmed; the cause and source of the inflammation needs to be identified and the effect of water levels on the presence and concentration of pathogens and toxins needs to be established. These factors may strongly influence the reproductive rate, growth performance, and energy requirements of the population. The evaluation variables to be determined in our study provide critical data to support the development of an individual based American alligator

model. The proposed experimental design should give accurate estimations of the evaluation variables for a single year; however, fluctuations in water levels require that data be collected over several years to provide Everglades Evaluation variables with a margin of error suitable for a reliable model which will allow planners to predict the effects of water levels on the alligator population.

The general objectives of the work are as follows:

1. Monitor the reproductive potential of the alligator population in the Southern Everglades (Everglades National Park) over a 5-year study period.
2. Monitor the prey quality over the study period.
3. Monitor egg quality over the study period.
4. Monitor health status of the alligators over the study period.
5. Determine associations between reproductive potential, prey quality, egg quality, and health status over the study period.

Random samples of 145 eggs from different clutches were collected in the Southern Everglades. Forty-one eggs were determined to be infertile or had very early embryonic death. Hatch rate for the fertile eggs and stage of embryonic deaths were recorded. Samples of 144 eggs from the Rockefeller Refuge in Louisiana were used as controls. Egg statistics and growth performance of the hatchlings were determined for both experimental and control groups. Egg statistics (35 factors or variables) determined for 1997 will be compared with values determined in 1995 and 1996 and with the factors obtained from 15 areas (lakes and farms) over 10 years in 10 X 15 two-way ANOVA. The comparisons involved the 20 factors determined in over 7,000 observations. Health status of the Everglades alligators was determined in 1997. Blood samples were drawn from 16 animals from the Northern Everglades (conservation areas) and transmitters were implanted in the animals in order to track them. Thirty blood samples were taken from animals captured in the Southern Everglades (Everglades National Park) and 20 variables (clinical values) compared with animals raised in captivity but hatched from eggs collected in the Southern Everglades or Louisiana (45 animals). The values obtained for the three groups and normal values obtained from animals captured in other areas were compared.

A significant part of the funding for this research was provided from the U.S. Department of the Interior South Florida Ecosystem Restoration Program "Critical Ecosystems Studies Initiative" (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the "Across Trophic Level System Simulation" was also provided by the Environmental Protection Agency and the U.S. Army Corps of Engineers.

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Vegetative Characterization for Everglades Studies

By Virginia Carter¹, Nancy B. Rybicki¹, Justin T. Reel¹,
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The vegetative resistance to flow and the effects of sheltering from wind of different plant communities in the Florida Everglades combine with land-surface elevational differences and evapotranspiration losses to control the velocity, flow direction, water depth, and hydroperiod in Taylor and Shark River Sloughs. The major objectives of the work reported here were (1) to provide detailed information on species composition, vegetative characteristics, vegetative structure, and biomass for quantification of vegetative resistance to flow and the effects of sheltering from wind, and (2) to extrapolate this information to classify the vegetation regionally and to improve existing vegetation maps for use in surface-water models.

Water management decisions derived from predictive models are critical to successful restoration of the Everglades. Without accurate and precise accounting for vegetative characteristics at scales commensurate with model discretization, flow can not be simulated accurately. Two surface-water models are being developed for Taylor Slough; one covers most of the slough, including the mangrove/Florida Bay interface, and one covers only the upper part of Taylor Slough below the park road. In order to model the surface-water flow, it is necessary to extrapolate point measurements of velocity and surface-water slope made concurrently with characterization of vegetation to the entire model area. Vegetative resistance to flow can be expressed by either Manning's n or the Darcy-Weisbach friction factor, but these two coefficients must be related to the actual field characteristics of the vegetation through which flow occurs to provide the basis for accurate predictions of flow. Several steps and numerous experiments were necessary to develop and refine measurement techniques to quantify this frictional resistance/vegetative cover relation. Measurements of critical variables were conducted in a hydraulic flume as well as in the Shark River and Taylor Sloughs to define the effects of frictional resistance on regulation of flow.

Flume experiments: The initial measurements of resistance coefficients were derived from carefully controlled flow measurements. Uniform dense stands of sawgrass were grown in the 200-foot long, 6-ft wide USGS tilting flume at Stennis Space Center, Mississippi (Lee and Carter, 1996). In several series of experiments conducted at various flow depths, vegetative resistance was calculated from velocity, flow depth, and water-surface slope. During each experimental series, the vegetation in the flume was sampled to determine, as a function of distance from the bed or the sediment/water interface, the biomass per unit area, the number of stems and leaves per unit area, leaf and stem width, and leaf area index (LAI). Sponges were added in one series of experiments in order to simulate periphyton. Following the measurements of vegetative resistance, the flume was refitted to measure wind effects on flow when sawgrass was present.

Shark River Slough: Because the transfer of laboratory results to the field is a critical part of this research, two Shark River Slough sites were selected to provide sawgrass communities of varying densities in which to make water-velocity and surface-slope measurements. A total of forty-two 0.5-m-square vegetation quadrats were sampled in April and November 1996. Vegetation including periphyton was harvested in horizontal layers, 10-cm or 20-cm thick, from the soil/water interface through the water column to the top of the plants. Species composition, density, size, dry biomass, and LAI were determined for each layer. Quadrats were sorted into density-related vegetation classes based on species composition and biomass (excluding periphyton). Composite profiles (layer by layer

means) were determined for each class. The 42 quadrats fell into nine different classes; rush and mixed sawgrass/rush classes were generally sparse or medium density, whereas sawgrass fell into four density classes, and cattail was very dense.

Taylor Slough: For modeling efforts in Taylor Slough, vegetation was sampled on three east-west transects across the slough. Sampling and processing were similar to, but slightly more detailed than, that in the Shark River Slough, and the quadrats were grouped into the same classes as in Shark River Slough. Composite layer-by-layer profiles were determined for each class. Two factors complicated the relation of biomass to velocity, dead plant material and periphyton. Large amounts of dead material or litter were mixed with the plants and, as generally calculated, LAI estimated only the live or total standing surface area opposing horizontal flow. We are developing a method for incorporating the dead litter, which is nonuniform in size and shape, in the LAI calculation. Periphyton was present in horizontal layers or vertical sleeves surrounding individual leaves. Although periphyton was spatially and temporally unpredictable and generally associated with sparse to medium vegetation classes, it also was present in denser classes. It could be accounted for in the total biomass figures for individual quadrats or mean class composites, but complicated calculation of a class composite biomass by layer and could not be included in a LAI.

A geographic information system was developed to help assimilate and interpret available spatial data such as digital orthophotoquads, digital line graphs, and a 1993-94 Landsat vegetation classification map of southern Florida developed by the USGS and the University of Florida. Working with the 32-class Landsat image, color infrared aerial photographs, and other available maps, we recombined map classes to show the areal extent of vegetation types considered to have different roughness characteristics and thus different effects on flow velocity. Cross checking these map classes with actual ground vegetation and characteristics determined through sampling, we developed a final map product for use with surface-water models in Taylor Slough. With the more accurate flow simulations that these models can provide, water managers can more confidently and precisely control and manipulate water levels, flows, and hydroperiods.

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The South Florida High-Accuracy Elevation Data Collection Project

By Gregory. B. Desmond¹

ISSUE DEFINITION

Sheet flow and water surface levels in South Florida are very sensitive to changes in elevation because of the region's expansive and extremely low-relief terrain. Hydrologists have determined that the minimum vertical accuracy requirement for elevation data used as input to hydrologic models is ± 15 cm. This requirement is complicated by the fact that the surface being measured in inundated wetlands is the water/substrate interface, which is often soft muck. Further, since the surface being measured is obscured by water and vegetation, the application of remote sensing techniques to derive these data (for example, photogrammetric stereo correlation and profiling, light detection and ranging, and interferometric synthetic aperture radar) is not possible. Traditional spirit-level surveying is not feasible either because of the very large area to be surveyed and because of cost and time constraints. Therefore, the primary issue is how to accomplish topographic surveys and provide elevation data over large areas of the inhospitable Florida Everglades and adjacent lands--that is, surveys and data that meet the stringent vertical accuracy specification required for hydrologic modeling.

BACKGROUND

The main objective of this project is to derive very accurate elevation data using state-of-the-art differential global positioning system (GPS) technology covering large regions specified by program hydrologists. The elevation data sets being generated by this project are the most accurate ever produced for the Everglades and surrounding environs. These data will be used in developing digital elevation models (DEM's), which in turn will be used to parameterize hydrologic models to simulate and predict water flow direction, depth, velocity, and hydroperiod. Water resources and land management decisions will rely on these models, so it is imperative to use the most accurate elevation data available to achieve meaningful results.

Techniques are being developed and used to collect and process GPS derived elevation data that have a vertical accuracy of 15 cm or better referenced to the North American Vertical Datum of 1988. The primary data collection strategy is to use the helicopter-based airborne height finder (AHF), developed by the U.S. Geological Survey (USGS), to collect data and produce elevation points spaced approximately 400 m apart throughout the Everglades National Park and other inaccessible areas. Data collection in areas accessible by airboat, all-terrain vehicle, or truck, is also being accomplished through a USGS contract with the private sector. A second major goal of the project, now completed, was the surveying and positioning of very accurate elevation reference marks to support data collection by the Florida Bay Marine Monitoring Network (MMN). The MMN, consisting of 29 instrumented platforms and gages distributed throughout Florida Bay, collects data on water levels as well as other hydrodynamic and meteorological variables. For the first time, these elevation marks allow all the MMN water levels to be referenced to an accurate datum so that water-level comparisons between gages can be more accurately determined.

STATUS/PROGRESS TO DATE

The project began as an interagency effort (USGS, U.S. Army Topographic Engineering Center (USATEC), and National Geodetic Survey) that was undertaken in fiscal year 1995 to demonstrate whether the new on-the-fly differential GPS (DGPS) technology could be used to perform topographic surveys that meet the requirements for high-accuracy elevation data. This demonstration project used airboats and a truck to collect DGPS data in wetland and residential areas, and the results proved very successful. However, large areas in the region, especially Everglades National Park, are not accessible by ground transportation. Therefore, another approach was needed for areas that are only accessible by helicopter. To meet this need, the AHF was engineered and fabricated. A second demonstration project using the AHF was conducted in fiscal year 1997. Again the results proved successful, and the AHF has since been undergoing evolutionary modifications resulting in the fabrication of an improved second system.

Since the beginning of the project, significant parts of eighteen 7.5-minute quadrangles have been surveyed by both government and contract survey parties, and field work is continually progressing. By the close of fiscal year 1999, it is estimated that parts of more than two dozen quadrangles will have been surveyed, including complete coverage of the Southern Inland and Coastal System model study area within the Everglades National Park. Lastly, the survey of the MMN water-level gage reference marks was completed in fiscal year 1997 and required survey resources from three agencies, the USGS, USATEC, and the National Park Service, and more than 1,700 hours of field work to complete.

FUTURE EFFORTS

Future efforts will include the continuation and expansion of ongoing field data collection and processing work. Accuracy assessments of the growing data sets will be greatly increased. It will also be necessary to expand the existing vertical geodetic control network for use as vertical reference points during AHF and airboat data collection operations and other surveying applications. An evaluation of light detection and ranging technology for deriving elevation data for agricultural lands is planned as well. Lastly, a patent application for the AHF is being investigated.

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The South Florida Land Characterization Project

By Gregory B. Desmond¹, John W. Jones¹, and George P. Lemeschewsky¹

ISSUE DEFINITION

Many South Florida stakeholders from government, private industry, environmental, and citizen sectors are collaborating in an effort to return the Florida Everglades system to its “natural state” in terms of restoring its values and functions as an integrated wetland system. Research into the measurement and modeling of water movement and other hydrologic processes is a primary scientific need in support of Everglades restoration. To accurately simulate surface water hydrology in South Florida, scientists must determine the variation in vegetation cover and the role vegetation plays in removal of surface water, resistance to surface water flow, and water quality. The objective of this research is to develop and apply innovative remote sensing and geographic information system techniques to characterize and map the distribution of vegetation and related hydrologic variables, such as evapotranspiration, through space and over time. This work will provide insights regarding the role South Florida vegetation plays in the redistribution of rainfall and surface flow inputs as well as the cycling of nutrients and other materials in the Everglades waters. It will contribute to our understanding of hydrology at large scales. Finally, it will lay the foundation for monitoring the effects of restoration on Everglades flora. These benefits are vital in building the understanding required to properly monitor, simulate, and manage the unique Everglades wetland resource.

BACKGROUND

The extrapolation of processes typically measured or modeled at point locations or at microscales to macroscales is an extremely difficult undertaking. However, this capability is needed to identify the important components of the natural system, quantify the impacts of human activity on the system, forecast system behavior, and monitor the effects of restoration actions. This work will develop the techniques and produce the data sets necessary to conduct hydrological modeling (surface water flow and water budget) at the regional scale. Additionally, success in developing periphyton mapping techniques would produce a critical new tool for biogeochemical and water quality research.

In situ and remotely sensed data from numerous platforms and sensors, each possessing different spatial, temporal, and spectral resolution, will be processed, analyzed, and combined to produce information about biophysical variables (for example, vegetation species composition, vegetation density, vegetation structure, and components of the surface energy balance), as well as image maps of South Florida. These data will be evaluated for their utility in specific modeling and monitoring contexts. Image map products will be developed to convey the results of this work and to portray current vegetation conditions in South Florida to the broadest audience possible.

STATUS/PROGRESS TO DATE

The overall task has been divided into four primary components with specific objectives and general classes of clients. Component one concerns the regional extrapolation of point evapotranspiration measurements and the role of vegetation in surface-water evaporation. Component two is aimed at vegetation-density mapping for resistance to flow modeling. Component three is a pilot

study of periphyton mapping techniques using hyperspectral remote sensing capabilities. The fourth component is the development of new, large scale image maps of the Southern and Inland Coastal System model study area within the Everglades National Park.

For each component, the U.S. Geological Survey (USGS) is systematically developing, evaluating, and applying the techniques that yield the most appropriate, spatially distributed information possible on the vegetation, climate, and hydrologic variables of interest to South Florida project scientists. For example, the Priestly-Taylor method is being evaluated as a means of estimating Everglades evapotranspiration without the need for extensive and costly data collection (see German, this volume). This method has been modified to use remotely sensed inputs of leaf area index (LAI) in environments quite different from South Florida. Although it is not yet clear whether LAI can be accurately measured for all dominant vegetation types in the Everglades environment using remote sensing, we have detected a strong relationship between sawgrass biomass and high spatial resolution remotely sensed indexes. Such analysis is possible given the combination of field campaigns (to provide ground truth information for data calibration and accuracy assessment) and extensive technique development that we are applying in each project component.

Remote sensing data from multiple sensors of differing spatial and spectral resolutions have been collected and are being processed. New image data fusion tools that maximize information content to support the interpretation of biophysical fields and yield improved image maps have been developed. To improve machine techniques for vegetation density mapping, scientists developed a new, artificial neural network technique that increases the spatial resolution of thermal-infrared imagery. Collaborative use of the resulting products will allow the evaluation of their utility for process modeling and environmental monitoring while facilitating outreach and technology transfer.

FUTURE EFFORTS

Since the capability to map LAI would contribute to widespread use of the Priestly-Taylor method and perhaps to the vegetation density mapping component, development of LAI estimation techniques at multiple scales using remote sensing will be an important research thrust in the near future. Information products and techniques developed through this project will be transferred to other scientists and management agencies by means of technical reports, existing program public information outlets, and other professional publications and meetings. Selected information produced through this effort (for example, satellite image maps) will be reproduced in sufficient quantity to allow wide distribution to both specialized users and the general public, thus providing increased understanding of the region and the role of the USGS in addressing scientific and management needs. Examples of upcoming major products are hard-copy maps, digital database layers of vegetation and hydrologic variables, CD-ROM's of derived information, and knowledge regarding the scaling properties of various surface features and processes.

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Geophysical Mapping of Saltwater Intrusion in Everglades National Park

By David V. Fitterman¹ and Maria Deszcz-Pan¹

Helicopter electromagnetic (HEM), transient electromagnetic (TEM), and borehole measurements have been used to develop a detailed three-dimensional picture of the extent of saltwater intrusion in Everglades National Park (ENP). These results are of value in assessing the effect of past water management practices on the Everglades. The influence of manmade structures on surface-water and ground-water flows is seen in detail. These data serve as a baseline for mapping changes in saltwater intrusion that result from restoration activities.

Helicopter electromagnetic surveys and transient electromagnetic soundings have been used to obtain formation resistivity throughout the study area. The HEM surveys provide closely spaced samples (10 m along flight line with 400-m flight line spacing). The TEM soundings provide greater depth of exploration and better model resolution than the HEM data; however, the sampling interval is much coarser (one sounding per 25 km²). The HEM data are interpreted as layered earth models at each measurement point and displayed as formation resistivity at selected depths. The TEM data are also interpreted as layered earth models.

The geophysical models can be used to estimate water quality. Water quality can be evaluated in many ways, ranging from visual observations of clarity to detailed chemical analyses of surface and well samples. Electrical conductivity lies in the middle of this analysis spectrum, providing a rapid technique when the primary concern is the concentration of dissolved ions. Electrical conductivity is a superb indicator of whether seawater is present in the surficial aquifer under the Everglades because of the large difference in chloride ion concentration between the fresh, surface water in the Everglades (40 mg/L) and the saltwater of Florida Bay, the Gulf of Mexico, and Biscayne Bay (15,000-35,000 mg/L). Geologic formations saturated with these two different fluids have formation resistivities that differ by factors of 50 to 100. Through the analysis of borehole induction logs from wells in and near ENP, the relation between measured formation resistivity and specific conductance (SC) of water samples has been established, allowing SC to be estimated from interpreted formation resistivities. An empirical relation between SC and salinity, which is valid for surface water in Dade County, is then used to estimate salinity.

The HEM data show a clear transition from freshwater to saltwater saturated regimes. This transition occurs from 8 to 20 km inland from the coast. The nature of this transition changes if tidal rivers are present. For example, to the west of Taylor Slough, where many tidal rivers are found, the landward extent of the transition is near the terminus of rivers, resulting in a jagged boundary. In Taylor Slough and eastward across the region draining toward Florida Bay and Barnes Sound, the interface is smooth because of large volumes of overland water flow and the absence of tidal drainages cutting deeply into the area. The lack of significant drainages to the east of Taylor Slough is due to the bedrock ridge that parallels the coast and forms a barrier to large stream formation. In addition to the freshwater/saltwater interface, the HEM data show other significant features: (1) a deep resistive zone in the middle of Taylor Slough where freshwater flow recharges the underlying aquifer, (2) variations in resistivity near raised roadways reflecting their influence on surface-water flow and aquifer recharge, (3) freshwater zones associated with infiltration from canals due to control structures and flow through cuts in the canals, and (4) historic saline water transport along a canal, formerly open to Florida Bay, adjacent to old Ingraham Highway.

The TEM soundings also locate the transition from freshwater to saltwater saturated zones. Interpreted formation resistivities from the TEM data fall into two clusters: 1) a freshwater saturated zone with resistivities in the range of 18 to 300 ohm-m, and 2) a saltwater saturated zone with resistivities of 2 to 7 ohm-m. On the basis of these resistivity values, the location of the freshwater/saltwater interface is mapped. The result agrees well with the HEM results but lacks the spatial detail of the HEM data because of the much coarser sampling interval.

An issue of great concern to ecosystem restoration is whether freshwater is flowing into Florida Bay. Although surface-water flows can be determined from measurements of streams leading to the bay, ground-water flows are more difficult to evaluate. Our HEM and TEM data sets can shed some light on possible ground-water flows. In the region from Florida Bay landward for distances of 5 to 10 km the HEM resistivity depth-slice maps show a uniformly low resistivity (1-2 ohm-m) zone from the surface down to a depth of at least 24 m. The base of the Biscayne aquifer, as mapped by drilling, is less than 24 m deep at locations where geophysical data are available. The low observed resistivities are indicative of saltwater saturation of the Biscayne aquifer. (Freshwater saturated zones would have resistivities of 30 ohm-m or more.) Similarly, the TEM results do not show the presence of a high resistivity zone in the Biscayne. While the geophysical models do not indicate the presence of a freshwater zone, thin resistive zones (1-2 m thick), that are not detectable and do not degrade the fit of the model to the data, could be embedded in the models. The likelihood of such zones existing over extended distances and being isolated hydrologically from the surrounding saltwater intruded aquifer is not considered to be of significance. Therefore, we conclude that there is no evidence of fresh ground water flowing to Florida Bay from the surficial aquifer.

The results of this project are of immediate value to managers who are responsible for restoration decisions because the results provide a detailed picture of saltwater intrusion and the effects of human activity on the hydrologic regime. Furthermore, this work provides a baseline for long-term monitoring of changes in the ground-water regime. Future geophysical surveys can be used to look for changes in subsurface conditions associated with planned modification of water deliveries to Everglades National Park. Airborne electromagnetic surveys are currently the only way to obtain rapidly a detailed snapshot of saltwater intrusion over this large, inaccessible area.

Through the course of this study, there has been ongoing collaboration with personnel from Everglades National Park, the South Florida Water Management District, the University of Miami, the U.S. Army Corps of Engineers, and the Florida Geological Survey. Our data have been used by these organizations to understand various aspects of the regional hydrology, to locate wells, and to plan hydrologic sampling activities.

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A Special Issue of the Journal *Estuaries* Dedicated to Long-Term Studies in Florida Bay

By James W. Fourqurean¹ and Michael B. Robblee²

Since 1987 when seagrass die-off first occurred in Florida Bay, a significant research effort has emerged within the Bay. The pace and diversity of this research have increased dramatically since 1994 and the beginnings of the Florida Bay Research Program and the establishment of the Federal Taskforce for Restoration of the Everglades Ecosystem in South Florida. Scientific review of the Florida Bay Research Program has always been a high priority of the Florida Bay Program Management Committee (PMC) which was established to coordinate research in Florida Bay. Results emerging from this research program, especially recent studies, are now becoming available for publication in the peer-reviewed literature. To facilitate this process the PMC sponsored a special issue of the journal *Estuaries* devoted to long-term studies in the Florida Bay ecosystem. These long-term studies serve as a foundation upon which future changes resulting from restoration activities can be evaluated.

Funding for this research was provided largely by the Department of Interior's South Florida Ecosystem Restoration Program's Critical Ecosystem Studies Initiative and in part from USGS Florida Caribbean Science Center funds for the Empirical and Modeling Studies in Support of Florida Bay Ecosystem Restoration Program.

The following papers will appear in *Estuaries* 22:2 in May 1999:

1. Fourqurean, J.W., and Robblee, M.B., Florida Bay: a history of recent ecological changes.
2. Halley, R.B., and Roulier, L.M., Reconstructing the history of eastern and central Florida Bay using mollusk-shell isotope records.
3. Brewster-Wingard, G.L., and Ishman, S.E., Historical trends in salinity and substrate in Florida Bay: A paleoecological reconstruction using modern analogue data.
4. Swart, P.K., Healy, G., Greer, L., Lutz, M., Saied, A., Anderegg, D., Dodge, R.E., and Rudnick, D., The use of proxy chemical records in coral skeletons to ascertain past environmental conditions in Florida Bay.
5. Rudnick, D.T., Chen, Z., Childers, D.L., Boyer, J.N. and, Fontaine, T.D., Phosphorus and nitrogen inputs to Florida Bay: the importance of the Everglades watershed.
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15. Mazzotti, F.J., The American crocodile in Florida Bay.

Editorial Panel

James W. Fourqurean, Southeast Environmental Research Program and Department of Biological Sciences, Florida International University; Michael B. Robblee, U.S. Geological Survey, and Linda Deegan, The Ecosystems Center, Woods Hole Marine Biological Laboratory.

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Computer Simulation Modeling of Intermediate Trophic Levels for Across Trophic Level System Simulations of the Everglades/Big Cypress Region

By Michael Gaines¹, George Dalrymple², and Donald L. DeAngelis³

This work has involved the modeling of intermediate trophic levels in the Everglades ecosystem as part of the Across Trophic Level System Simulation (ATLSS) package of models. The fish and herpetological communities play pivotal roles in the Everglades, acting as principal forage sources for such top consumers as wading birds and alligators.

Fish modeling: The purpose of this work was to develop a model of the dynamics of a key functional group of fishes in the freshwater in the Everglades/Big Cypress ecosystem. The work performed here developed a predictive model for the numbers, size and age structures, and biomass per unit area of small fishes in any selected part of the freshwater marsh. A key factor included in the model is the seasonal cycle of water depth. This environmental seasonality is echoed in patterns of production of fish biomass, which, in turn, influences the phenology of other components of the food web, including wading birds. Human activities, such as drainage or other alterations of the hydrology, can influence these natural cycles and result in changes in the fish production and the higher trophic levels dependent on this production. In the model the seasonal pattern of fish production in the freshwater Everglades/Big Cypress region is simulated on 5-day time steps. The model illustrates the temporal pattern of production through the year, which can result in very high densities of fish at the end of a hydroperiod (period of flooding), as well as the importance of ponds and other deep depressions, both as refugia and sinks during dry periods. The model indicates: (1) there is an effective threshold in the length of the hydroperiod that must be exceeded for high fish-population densities to be produced, (2) large, piscivorous fishes do not appear to have a major impact on smaller fishes in the marsh habitat, and (3) the recovery of the small-fish populations in the marsh following a major drought may require up to a year. The last of these results is relevant to assessing anthropogenic impacts on marsh production, as these effects may increase the severity and frequency of droughts.

This small-fish model has been extended to cover the whole Everglades landscape, in 500 x 500 meter cells, by the University of Tennessee. This predicts the distribution of fish number and biomass density across the Everglades landscape on 5-day time steps and allows the calculation of a breeding potential index for wading birds, for which fish is a main dietary component. The model is currently providing output that is being included in the ATLSS “Model Outputs for the Central and Southern Florida Comprehensive Review Study” (or C&SF Restudy). In addition, this model will be integrated in 1998 into the wading bird breeding colony models that are nearing completion.

Reptile and amphibian modeling: A food web “submodel” of the amphibians (frogs and salamanders) and reptiles (snakes and turtles) has been developed. The model has been parameterized for three ecosystem types within the Everglades/Big Cypress region, using data supplied by George Dalrymple. Linear programming methods have been used to ensure the consistency of these data in predicting biomass standing stocks and fluxes. The reptiles and amphibians of this submodel are important food sources of the alligators and wading birds. The purpose of the model is to predict the dynamics and production of these taxa across the landscape of the Everglades/Big Cypress under a variety of hydrologic scenarios. A primary reason for modeling them here is to predict the availability of biomass to higher trophic levels (for example, particularly alligators). In addition, the model will

be able to predict the expected year-to year variability in these populations under realistic climatic conditions, and their responses to changes in system hydrology. This submodel will also be used to provide input data for an alligator model now in preparation.

Associated field studies (alligator diets): To help link these intermediate trophic levels with a key top predator, a four-year study of the diet of the alligator, *Alligator mississippiensis*, was conducted in the Everglades. The first three years of this study led to the amassing of a data set on alligator diets in the central slough area of the southern Everglades. These data will be extremely valuable in attempting to predict the responses of the alligator population to changes in landscape hydrology. On the basis of observations of the investigator and other researchers, the condition of alligators in the slough (away from canals) is far worse than that of alligators living in canals. This has been hypothesized to be a result of more food available to alligators in the canal. Stomach contents of alligators from the canals will be sampled to determine diets through the year, and compared with the diets of alligators in the slough. During the three years of this study, the investigator has tagged approximately one thousand alligators. These alligators are currently being recaptured in another project and statistical analysis will be used to estimate both the current total population size and mortality rate of alligators in the central slough area.

A significant part of the funding for this research was provided from the U.S. Department of the Interior South Florida Ecosystem Restoration Program “Critical Ecosystems Studies Initiative” (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the “Atlas Tropic Level System Simulation” was also provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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South Florida Ecosystem Database Development

By Linda Geiger¹, Jo Anne Stapleton², Roy Sonenshein³,
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The USGS initiated the South Florida Ecosystem Program (SFEP) in fiscal year 1995 for the purpose of gathering hydrologic, cartographic, geologic, and biologic data that relate to the mainland of South Florida, Florida Bay, and the Florida Keys and Reef ecosystems. The USGS is developing a distributed spatial database as part of the SFEP; this database will be used to store and maintain metadata and geospatial data sets produced by Federal, State, regional, and local agencies participating in the South Florida Ecosystem Restoration effort. Preexisting data sets relevant to the restoration effort also will be included. The database development project consists of four parts: (1) a metadata database, (2) a data exchange, (3) a database, and (4) a web site summarizing the USGS SFEP and providing access to the metadata and project data. A graphical interface to the data using a geographic information system (GIS) is in the planning and design phase. A significant goal of this database project is to provide continuing access to metadata and data for researchers from many agencies working in South Florida.

The approximately 50 research projects that are part of the SFEP research effort have been documented using the Federal Geographic Data Committee (FGDC) metadata standard and metadata files are available through the SFEP public web site, <http://sflwww.er.usgs.gov>. Metadata are defined as data about data; metadata describe the content, quality, availability, and other characteristics of data. Project metadata allow other researchers, managers, and other interested persons to discover what research is being done and to assess the suitability of the data for a particular application. Also, by documenting what is already in progress, duplication of research efforts can be avoided.

The documentation of data sets (dataset metadata) from the USGS research is underway. Several methods of generating metadata have been explored and evaluated. Word processing software in conjunction with a preparer and metadata parser have been used to create the bulk of the existing records. Evaluation and testing of a commercial metadata software package is in process. The output from either method will be a set of metadata records in html and text formats that can be indexed and searched through a clearinghouse and through the South Florida Ecosystem web site. The metadata link directly to the available data sets on the data exchange and will be retrieved with the data sets.

The data exchange is now online and available through the SFEP public web site or directly at URL <http://fl-water.usgs.gov/exchange/exchange.html>. This web site accesses an ftp site which facilitates the rapid exchange of raw datasets from known project chiefs. Datasets are made available through the data exchange before they are entered into the database. These datasets are considered provisional until they are published in a formal USGS publication. Links are provided to other categories of ancillary information such as dataset format, methodology, site location maps, graphs, and summaries.

The SFEP database is online and available through the SFEP public web site or directly at URL <http://www.envirobase.usgs.gov>. All data being collected by the USGS as part of the SFEP will be included in the database, either in data tables or as related files. The database currently holds information for 51 projects, 43 stations, and more than 600,000 data values. This is a dynamic database with new projects and data added daily.

A web-based interface to the database is online and available through the SFEP public web site or directly at URL <http://www.envirobase.usgs.gov>. This interface allows direct query and retrieval of project information, data collected, findings, and summaries. Project information can be retrieved

by area or agency of interest, investigator, or by topic of interest. Data collected can be retrieved by date, geographic area of interest, and by parameter collected. Data is output as a file, a graph, or on screen and can be plotted on a base map.

More than 30 fact sheets and other publications describing USGS South Florida research projects are available on the SFEP public web site. More than 100 metadata files from research on the South Florida ecosystem, including Florida Bay and the Everglades, are available for searching on the web site. Ancillary information such as project chief and site photos, summaries, charts and graphs, and posterboards are brought online daily. Links to related sites maintained by the USGS and other agencies are included.

The graphical interface will provide an additional tool for helping researchers to obtain data from the database. The graphical interface consists of a menu-driven system to view and query the database. Map graphic tools (menus) allow the user to pan and zoom to a geographic area of interest, select map layers to be displayed, identify map attribute information, and select and view data collection sites by location and attribute. These attributes include station name, station identification number, parameters of data being collected, frequency of collection, and period of record. Data sets associated with the selected sites can then be retrieved from the database.

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Evapotranspiration Measurement and Modeling in the Everglades

By E.R. German

A network of nine sites (seven vegetated sites and two open-water sites) was established to provide evapotranspiration (ET) and related meteorological data in the Everglades. The sites are representative of the natural Everglades system in terms of plant communities, duration of water inundation, and geographic extent. Site locations and other details, including study objectives, methodology, and timeframe, are described in a previous publication (German, 1996).

Half-hourly ET totals for January 1996 through December 1997 were calculated and used to calibrate models of ET for each site. First, data were first carefully screened to eliminate periods when sensors were malfunctioning. Also, periods when temperature and vapor-pressure gradients were too small to be accurately determined, as typically occurred at night, were identified and excluded from model calibration. The site models were developed using a modified Priestley-Taylor relation of the following form:

$$\lambda E = \alpha \Delta (R_n + G + W) / (\Delta + \gamma) \quad (1)$$

where λE is the latent heat (energy equivalent of ET), α is the Priestley-Taylor coefficient, Δ and γ are related to atmospheric temperature and pressure, and the terms R_n , G , and W are measured inputs or outputs of energy. Specifically, R_n is the net solar radiation, G is soil heat flux, and W is energy from cooling or heating of standing water. The Priestley-Taylor coefficient (α) typically is not constant, and in these models was expressed as

$$\alpha = C_1 \times R_i + C_2 \times S + C_3 \quad (2)$$

where R_i is incoming solar energy (measured using a pyranometer), S is the depth of water on the land surface, and C_1 , C_2 , and C_3 are coefficients determined by using least-squares regression to minimize the difference between measured latent heat and latent heat calculated using equation (1). The site models typically have coefficients of variation (CV) of 15 to 30 percent for the half-hourly ET totals, which are equivalent to about 2 to 4 percent for daily totals.

Regional models were then developed for the natural Everglades system. The seven individual site models for the vegetated sites were combined using least-squares regression into a single relation that can be used to estimate ET anywhere in vegetated areas as a function of available energy, solar intensity, and stage. This regional model is applicable to sawgrass marshes, wet prairies, and cattail areas. In open-water areas, the regional model consists of assigning α in equation 1 a constant value of 1.26, the theoretical maximum value. Neither of these regional models is intended for use in saltwater areas, forested areas, or agricultural areas.

Preliminary measured and simulated mean annual total ET for 1996-97 was calculated for all sites. In calculating the measured ET totals, simulated ET from the site models was used to estimate ET for intervals when air temperatures and vapor pressure gradients were missing because of sensor malfunction, or when the gradients were too small for accurate measurement. Simulated ET mean annual totals were computed entirely from the regional models.

The measured average annual total ET at the nine sites ranged from 42.3 inches at a vegetated site (C111) to 56.0 inches at an open-water site (Enr). These differences mostly reflect availability of water and density of vegetative cover. At site C111 (data available for 1997 only), the water was below land surface nearly half of the days, whereas at the open-water sites water was always above land

surface with no emergent vegetation. Among the predominately-wet vegetated sites, the measured annual total ET ranged from 43.7 to 50.6 inches. These differences seem to be related to vegetative density and depth of water on the land surface.

ET at another site, dominated by cattails, was noticeably lower than at the other sites where water level was always above land surface. This relatively low ET at the cattail site could be related to the carpet of duck weed that often completely covered the water surface, perhaps isolating the water surface from the atmosphere to some degree and thus retarding evapotranspiration. Another possibility is that accumulations of dead cattail stalks could have intercepted significant amounts of solar radiation and increased the transport of convective heat relative to latent heat.

The ability of the regional models to simulate ET is indicated by the comparison of the measured and simulated annual ET. Absolute values of the differences between simulated and measured mean annual total ET at the nine sites ranged from 3.7 inches to 0.4 inch, and averaged 1.8 inches for all sites. Improved estimates of ET allow for more accurate simulation of water flows, a very important factor in restoration of the Everglades.

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Overview of the Across Trophic Level System Simulation (ATLSS) Program

By Louis J. Gross¹ and Donald L. DeAngelis²

A basic component of restoration planning in South Florida has been the development and use of computer simulation models for the major physical processes driving the system, notably models for freshwater hydrologic dynamics as it is affected by alternative human control systems and non-controlled inputs such as rainfall. The major objective of the ATLSS (Across Trophic Level System Simulation) Project has been to utilize the outputs of such physical systems models to drive a variety of models that attempt to compare and contrast the relative impacts of alternative hydrologic scenarios on the biotic components of South Florida. The biotic models are constructed at varying levels of spatial, temporal and organismal resolution, and have focused to date on intermediate and upper trophic level biotic components. The principal goal is to provide a rational, scientific basis for developing relative rankings of hydrologic scenarios as input to the planning process, and through this to aid development of appropriate monitoring and adaptive management schemes.

ATLSS is constructed as a multimodel, meaning that it includes a collection of linked models for various physical and biotic systems components. The component models utilize a variety of approaches and operate at different spatial and temporal resolutions, depending upon the level of detail appropriate for the organisms being addressed as well as limitations imposed by inadequate data to realistically model the system. The ATLSS models all are linked through a common framework which allows for the necessary interaction between spatially-explicit information on physical processes and the dynamics of organism response across the landscape. ATLSS models all include some mechanistic components, though some are considerably more detailed in the level of description of the organisms involved. ATLSS outputs all are interpreted in a relative assessment framework, in which an alternative is compared to a base scenario.

The ATLSS hierarchy starts with models which translate coarse resolution hydrologic information to a finer resolution appropriate for biotic components that operate at spatial extents much smaller than the 2-mile resolution of the main hydrologic model. The development of such a high resolution hydrology relies upon vegetation maps and the associated limitations on hydroperiod associated with these, to characterize a 28.5-meter resolution topography (pseudotopography) chosen to preserve the volumes of water derived from the 2-mile resolution hydrology model.

The ATLSS hierarchy next includes Spatially-Explicit Species Index (SESI) models which make use of the spatially-explicit, within-year dynamics of hydrology to compare the relative potential for breeding and/or foraging across the landscape. SESI models are viewed as approximations which are useful in coarse evaluations of scenarios and are an aid in interpreting the more detailed models. SESI models have been constructed and applied during the Central and Southern Florida Comprehensive Review Study (Restudy) to the Cape Sable Seaside Sparrow, The Snail Kite, Short- and Long-Legged Wading Birds, and White-tailed Deer, with an additional model for Alligators now near completion.

Considerably more detailed models have been developed for the distribution of functional groups of fish across the freshwater landscape. This model considers the size distribution of large and small fish as important to the basic food chain which supports wading birds. It has been applied to assess the spatial and temporal distribution of availability of fish prey for wading birds. Individual-based models, which track the behavior, growth and reproduction of individual organisms across the landscape, have been constructed for the Cape Sable Seaside Sparrow, the Snail Kite, The White-tailed Deer, the Florida Panther and various Wading Bird Species. The models include large mechanistic

detail, and their outputs may be compared to the wide variety of organism distribution data available, including that from radio collared individuals. An advantage of these more detailed models is that they link each individual animal to specific environmental conditions on the landscape. These conditions (for example, water depth, food availability) can change dramatically through time and from one location to another, and determine when and where particular species will be able to survive and reproduce.

The ATLSS models are constructed in an object-oriented framework, in order to allow flexibility in modification and reuse of code. The models are written in C++, and much of the visualization utilizes the PV-Wave package. ATLSS models have been developed and tested in close collaboration with field scientists who have years of experience and data from working with the major animal species of South Florida.

The focus of ATLSS to date has been on the freshwater systems, with emphasis on the intermediate and upper trophic levels. The ATLSS structure was purposely formulated to provide for extension to estuarine and near-shore dynamic models once physical system models for these regions are completed. This would involve the construction of a variety of additional models for the biotic components. A further effort at lower trophic levels in the freshwater regions is needed to account for the impact of hydrologic plans on vegetation change and associated nutrient fluxes. Closely linked with these would be models for the effects of major disturbances to the system, including fire and hurricanes. Finally, ecotoxicological models coupled to transport models for toxicants such as mercury may be readily incorporated into the biotic components already constructed.

A significant part of the funding for this research was provided from the U.S. Department of the Interior South Florida Ecosystem Restoration Program “Critical Ecosystems Studies Initiative” (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the “Atlas Tropic Level System Simulation” was also provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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ATLSS Landscape Fish Model

By Louis J. Gross¹ and Donald L. DeAngelis²

The Across Trophic Level System Simulation (ATLSS) Landscape Fish model (ALFISH) has as its main objective the capability of comparing in a spatially-explicit manner the relative effects of alternative hydrologic scenarios on freshwater fish densities across South Florida. Another objective is to provide a measure of the dynamic, spatially-explicit food resources available to wading birds. By providing a model for the key resource base for wading birds, ALFISH allows the linkage of the hydrologic effects on fish densities with models for wading bird foraging. ALFISH has been developed in regular consultation with several field biologists and has made use of a variety of data sources on fish distributions to estimate parameters.

ALFISH operates by splitting the landscape into spatial grid cells, of size 500 m x 500 m, characterizing the within-cell variability in water depth in a statistical manner. Within each cell, there is a distribution of elevations based upon an average hypsograph obtained by averaging data from a number of locations. Cells also contain permanently wet areas of small size, called “ponds,” with the remaining cell areas, subject to periodic dry down and reflooding, referred to as the “marsh areas.” Fish densities change within cells between areas of various depths as a cell dries down or rewets, since differing fractions of area within cells will be at differing water depths. Adjacent spatial cells are coupled in the model by movements of fish density between cells due to differences in relative fish densities or differences in relative water depth between cells.

The main inputs to ALFISH are hydrology data at a 500-m resolution from the ATLSS High Resolution Hydrology Model, time of year, and food resources available from lower trophic levels. For the application of ALFISH to the Restudy, all lower trophic level resources are assumed constant, independent of hydrology. The time step of the model is 5 days and the study area includes all of the region for which hydrology data are being produced for each scenario, with some outputs being computed only for particular subregions within the study area.

For each cell a modified version of the fish population model originally developed at the University of Miami for a single spatial cell is used to describe the main fish functional groups. ALFISH considers two fish functional groups: Small Fish, which includes all fish species with a maximum possible length of 7 cm, and Large Fish, which includes all fish species with maximum lengths of greater than 7 cm. ALFISH treats the fish functional groups as an age- and size-structured model. The fish in each functional group grow in size every 5-day time step. The age of maturity and the fecundity are unique to each functional group. Four causes of mortality are included: (1) Background mortality, or the natural mortality of an uncrowded population, which is dependent on fish age class, but is independent of population size; (2) density-dependent mortality from starvation; (3) loss due to predation from other functional groups; and (4) death due to dry down in which some fraction of fish density do not successfully reach deeper water as a cell dries.

Movement in ALFISH has two phases. First, within-cell movement takes place, allowing fish density to move between the pond and the marsh areas of various depths within a particular cell. Secondly, fish density can shift between the marsh areas of adjoining cells, based on differences between water depth and fish densities in these cells.

ALFISH has been applied to all the major Restudy scenarios, with comparisons made to F2050 as the base scenario. The ALFISH outputs include a wide variety of maps of both average and single time period total fish densities across the region, maps of fish densities available to wading birds (for example, fish in appropriate size ranges and at appropriate waters depths to be available to wading

birds), various time series of fish densities averaged across various subregions, time series of histograms of the size distribution in particular subregions, and tables summarizing the total fish number densities broken down by basin and by year.

Several major modifications to ALFISH are either ongoing or planned. The ongoing efforts include incorporation of maps of alligator hole distributions, use of these to appropriately estimate the area in ponds across the model region, performing uncertainty analysis to ascertain whether the data are consistent with fish refuges during dry-down in addition to ponds, and incorporation of ALFISH with an individual-based wading bird model. Planned extensions of ALFISH include linkage to a dynamic model of lower trophic levels that is hydrologically driven and production of a model appropriate for estuarine regions.

A significant part of the funding for this research was provided from the U.S. Department of the Interior South Florida Ecosystem Restoration Program “Critical Ecosystems Studies Initiative” (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the “Atlas Tropic Level System Simulation” was also provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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Overview of ATLSS Spatially Explicit Index (SESI) Models

By Louis J. Gross¹ and Donald L. DeAngelis²

The Across Trophic Level System Simulation (ATLSS) package of models is designed to utilize varying levels of detail and data availability to assess the relative impact of alternative hydrological plans on the biotic components of South Florida. A key type of model within this package makes use of information on breeding and foraging requirements for species and how these relate to habitat and hydrologic conditions, but does not attempt to track in detail the population dynamics or behavior of individuals for these species. These are Spatially-Explicit Species Index (SESI) models which make use of the spatially-explicit, within-year dynamics of hydrology to compare the relative potential for breeding and/or foraging across the landscape. SESI models are viewed as approximations which are useful in coarse evaluations of scenarios and are an aid in interpreting the more detailed models. SESI models have been constructed and applied during the Central and Southern Florida Comprehensive Review Study (Restudy) to the Cape Sable Seaside Sparrow, the Snail Kite, Short- and Long-Legged Wading Birds, and White-tailed Deer, with an additional model for Alligators now near completion. These models have been applied on a regular basis during the Restudy to assess the relative effects of alternative scenarios compared to F2050 as the base scenario.

Habitat Suitability Index (HSI) models have been developed for many wildlife species, with the objective of evaluating the potential effects of management decisions which modify habitat conditions for these species. SESI models differ from traditional HSI models in that they:

- (1) have a temporal component and, thus, incorporate both static and dynamic landscape features;
- (2) are based on a “landscape structure” which, once established, can be used to model the responses of any species in the system; and
- (3) can provide a relatively easy means of comparing species responses to more complex ATLSS models, including process models, size-structured population models, and individual-based models.

SESI models are based on both static and dynamic landscape information. The first step in producing a SESI model is to provide a “landscape structure” using a Geographical Information System (GIS). This structure includes both static information (for example, surface elevations, aspect, soil type, vegetation type and structure, physical structures) and dynamic information (for example, changing water levels, fire, vegetation dynamics). The landscape is divided into equal-sized spatial cells, each with a suite of values that correspond to the parameters included in the model. The inclusion of static and dynamic information results in an interdependence of the values assigned to each cell.

The next step in developing a SESI model is to decide what aspect of the species' ecology will be used as the index. Often, when considering the effects of habitat management activities on only one species, breeding habitat - how much of the landscape will be suitable for successful breeding during the breeding season - is the most direct statistic for comparison. If the species has special breeding requirements that can not easily be incorporated into the structural landscape or if breeding is not spatially limited, another aspect of the species biology could form the basis of the model index. One additional aspect that we have used is foraging potential, in which site-specific information can be used to assess foraging success dynamically.

The ATLSS SESI models have involved both breeding and foraging aspects in developing appropriate index values. The Cape Sable Seaside Sparrow SESI model focuses on breeding rules, all based on the results of intensive field studies. These rules describe how the dynamics of hydrology affect the duration and spatial extent of the annual dry season during which the water level in any cell remains below the nesting threshold level. The index then estimates the potential number of breeding cycles in cells with appropriate levels of preferred habitat. The SESI model for the snail kite focuses on estimating appropriate foraging conditions during the kite breeding season for these raptors which are obligate predators of the apple snail. The requirements for appropriate foraging sites include:

- (1) having the potential for a substantial population of apple snails;
- (2) having surface water present; and
- (3) having surface water depths less than certain depths (or else the kites cannot locate and catch snails).

The ATLSS Wading Bird Foraging Conditions Index Model uses knowledge of how hydrologic factors affect the concentration and availability of food resources during the breeding season to compute a Foraging Conditions Index (FCI) for wading birds. The FCI is a composite index of spatial and temporal patterns. It expresses the effects of proposed hydrologic scenarios as changes in the spatial pattern of foraging potential over the model area for the simulation period. It calculates the FCI for two different types of wading birds: (1) a “long-legged forager” type with a feeding depth range of 5 to 35 cm and a long nesting cycle (during which a major water level reversal would cause nesting failure and decrease the index value to zero); and (2) a “short-legged forager” type with a feeding depth range of 0 to 20 cm and a shorter nesting cycle (with potentially multiple opportunities for nesting during a single dry season). The ATLSS White-tailed Deer SESI model also uses knowledge of how hydrologic factors affect the production and availability of food resources and the availability of dry bedding sites during the breeding season to compute an index for deer.

Several modifications are planned for the already constructed SESI models in addition to construction of new models. A SESI model for alligators is currently near completion and it is expected that there will be some SESI models constructed for the Florida Panther during the process of revising the individual-based Panther model. Planned extensions of to improving the current SESI models involves incorporation of methods to account for successional changes in habitat due to hydrology, as well the impact of fire.

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Computer-Based Tools for Managing and Modeling the Florida Panther Population Over the Landscape of South Florida

By Louis J. Gross¹ and Donald L. DeAngelis²

The mountain lion once ranged throughout the Southeastern United States, from the coastal plains to the mountains. This formerly widespread species is now represented by the small population of the Florida Panther that survives in the wildlands of South Florida. Recent studies have demonstrated that the public lands of South Florida (Everglades National Park and Big Cypress National Preserve) are probably inadequate to support a viable panther population. Over half the home range area for radio-collared panthers has been on private lands. Of the 43 panther monitored during the 1980's, only 4 ranged exclusively on public land. It has been estimated that public lands in South Florida would be able to support only 9 to 22 panthers, with doubt as to whether in-area reproductive capabilities could continue to sustain this number.

One of the primary tools for assessing the impact of the Everglades Restoration on the Florida Panther is the Deer/Panther Model being developed as part of the USGS Across Trophic Level System Simulation (ATLSS) modeling project. As currently configured, the ATLSS models are designed to operate over the region modeled by the South Florida Water Management Model, which provides the hydrologic input that drives the ATLSS models. A major deficiency of this modeling effort, with regard to assessing and managing the Florida Panther, is that the SFWMM region does not include some of the highest quality and most critical habitat for the panther. These critical lands include public and private lands to the west and north of Big Cypress National Preserve (BCNP). The public lands that are included in the SFWMM typically do not produce enough young panthers to maintain a viable population that can emigrate and colonize new areas. In fact, the current model area actually serves as a "sink" for young panthers produced by the breeding populations north and west of Big Cypress.

Until the region covered by the ATLSS Deer/Panther Model can be extended to include the breeding populations west and north of Big Cypress, it will be impossible to properly calibrate and test the Deer/Panther Model, and the model might be of little use for regional assessment and management of the Florida Panther. We propose to extend the area covered by the ATLSS Deer/Panther Model to include the core areas for activity and reproduction that lie outside the current boundaries of the SFWMM. As noted in a previous version of this proposal, carrying out this extension in a hydrodynamically exact manner would involve modification of the SFWMM 2- x 2-mile hydrology model. This would involve making use of historical satellite (LandSat) images to develop time series of hydrologic conditions and vegetation changes relevant to the quality of panther habitat.

Due to funding limitations, we here propose to develop only a very coarse hydrology model not hydrodynamically vigorous, but making use of estimates from other available models (including the NSM) to extend any particular scenario to the areas north and west of the BCNP. This will produce spatially and temporally varying estimates of water depth in this region, but without a full hydrodynamic linkage to the model which produced the particular scenario being investigated. This effort will require the following tasks:

The ATLSS Deer/Panther Model will be expanded to run over the added areas outside of the BCNP. This will allow direct comparison of ATLSS Deer/Panther output to panther radio-tracking data, much of which covers areas outside the boundaries of the WMM and current ATLSS models.

Visualization and analysis tools will be developed for analyzing panther radio-tracking data and comparing observations to ATLSS Deer/Panther model output over the entire range of panthers in South Florida.

A significant part of the funding for this research was provided from the U.S. Department of the Interior South Florida Ecosystem Restoration Program “Critical Ecosystems Studies Initiative” (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the “Atlas Tropic Level System Simulation” was also provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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Sea-Level Rise and the Future of Florida Bay in the Next Century

By R.B. Halley¹, E.J. Prager^{1,2}, R.P. Stumpf^{1,3}, K.K. Yates¹, and C.H. Holmes¹

During the next century, the physiography of Florida Bay will change due to a complex interplay between sediment production, transport, and accumulation and the local, relative rate of sea-level rise. Some estimates have predicted that the Bay will eventually fill with sediments and become part of the Everglades (Enos and Perkins, 1979). Others suggest erosion and removal of sediment in the Bay (Wanless and Tagett, 1989). Recent estimates of sediment production (Bosence, 1989; Halley and Yates, unpublished), transport (Stumpf and others, in press), and accumulation (Holmes and others, in press) indicate neither of these scenarios is correct. Rather, more subtle and complex changes will continue the slow evolution of the Bay that has characterized it this and the last century.

The bulk (60 percent) of Florida Bay sediments which have been accumulating for approximately four thousand years (Scholl, 1964) occurs in mud banks, with much of the remainder (38 percent) in flanking deposits that spread over lake floors in the central and western parts of the Bay. Islands, tidal channel deltas, and filled solution holes account for only a few percent of the sediment in the Bay. Geochemical and constituent sediment analyses demonstrate that the sediment has formed mostly from the biota living in the bay. About 90 to 95 percent is carbonate skeletal debris and 5 to 10 percent is organic debris, mostly mangrove and seagrass. There is a small detrital fraction, generally less than a few percent, consisting of quartz, clays and dolomite (Prager and Halley, 1997). Size analyses of surface sediments result in a sand/mud ratio of about 3:2, but analyses of cores indicate the bulk of the sediment contains more mud with a sand/mud ratio of about 1:5. The sandy surface sediments result from winnowing processes that preferentially transport mud to mud banks leaving a sand veneer over large areas of the Bay floor.

Sediment is continuously produced by living organisms and is, eventually, remobilized by erosion. Erosion occurs along unprotected shorelines, exposed mud banks, and areas recently denuded by seagrass mortality. Eroding islands show the most rapid erosion rates, with shoreline retreat rates of some islands approaching 1 m yr^{-1} . The presence or absence of seagrass is a first-order control of subtidal erosion and deposition. Some mud banks that erode on exposed margins are accreting on protected margins, causing a net migration on the order of 0.5 m yr^{-1} . Areas of seagrass mortality may expose extremely fluid mud to erosion, redepositing several centimeters of sediment per year.

Wave modeling and measurement help researchers to understand the complexities of erosion and deposition and the importance of seagrass. Waves form in the basins and propagate most effectively across basins with long axes parallel to the wind. Refraction effectively turns waves parallel to the banks. However, seagrass effectively dampens out wave energy along bank margins (Prager and Halley, in press). If seagrass is absent, significant erosion may occur in these areas. Although summer thunderstorms account for some erosion and turbidity, remote sensing studies indicate that winter cold fronts account for most of the turbidity and sediment transport in the Bay. Turbidity patterns also reveal a seasonally consistent west-central clear zone, indicating that little sediment from the central and eastern Bay escapes the estuary (Stumpf and others, in press). Only hurricanes are energetic enough to redeposit sediment on islands and along shorelines.

Sedimentation rates between 0.5 and 2 cm yr^{-1} have been measured from the accreting margins of mud banks (Holmes and others, in press). These rates are almost an order of magnitude greater than sea-level rise and indicate the mud banks can outpace sea-level rise. However, coring reveals that mud banks are keeping up to sea level, not catching up or becoming islands. It is hypothesized that seagrass

dynamics prevent the banks from growing above sea level. Periodic episodes of seagrass mortality, probably caused by excessive aerial exposure, limit the ability of the banks to accrete above the annual low tide.

Newly formed sediment is a minor contribution to the banks on the basis of studies using radiocarbon as a tracer of carbonate produced since thermonuclear atmospheric testing of the late 1950s and early 1960s, only a fraction of a percent of new carbonate sediment has been produced in the past 40 years. Although carbonate production rates are estimated in the range of 100s of gms m⁻² yr⁻¹ (Boscence, 1989), much of this production is redissolved (Walter and Burton, 1990). Net accumulation over the past 3,500 years has been approximately 0.2 mm yr⁻¹ (2.2 gms m⁻² yr⁻¹). These production rates are similar to carbonate productivity estimates calculated from alkalinity and pH measurements made during the summer of 1998.

Production rates of a fraction of 1 mm yr⁻¹, by themselves, are insufficient to keep up with sea-level rise. But the continuous redistribution of sediment, preferentially accumulating in seagrass on mud banks, will maintain the banks at approximately the annual low tide mark. The basins, on the other hand, will slowly deepen as sediment is transported by wave action and residual circulation to the margins of the mud banks. The deepening will approximate the rate of sea-level rise. The long-term evolution of Florida Bay, forced by sedimentation and sea-level change, define the context within which more recent changes such as seagrass die-off and algae blooms occur. It is important to consider recent ecological change in light of this dynamic setting.

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Hydrologic Exchange of Surface Water and Ground Water and Its Relation to Surface Water Budgets and Water Quality in the Everglades

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Concerns about the flow and chemical quality of water in the Everglades have opened new discussion on how best to manage the conveyance of surface water through this ecosystem. Plans call for improving chemical quality of water entering the compartmentalized basins of the north and central Everglades, called Water Conservation Areas (WCA's), as well as maintaining surface flows through WCA's to Everglades National Park. Several restoration efforts are already underway, including the construction of large constructed wetlands called Stormwater Treatment Areas (STA's) at the northern terminus of the Everglades to intercept agricultural drainage and to remove excess nutrients. Evaluating the success of ongoing restoration efforts and planning for future restorations depends on reliable hydrologic information, including a better understanding of the role of interactions between surface water and ground water. The purpose of the present project is to (1) quantify hydrologic fluxes between surface water and ground water in areas where limited prior information exists, and (2) use new estimates of hydrologic fluxes to improve the accuracy of hydrologic budgets and chemical mass balances for constituents such as mercury, sulfate, and nutrients. Investigations are underway in three principal areas. The first area is the 4,000-acre Everglades Nutrient Removal (ENR) area, a prototype STA; the second area is WCA-2A, a 105,000-acre basin with a long history of accumulating excess nutrients; and the third area is central Taylor Slough, where the goal of ongoing restoration efforts is to maintain southerly flows through the slough to Florida Bay while protecting chemical quality and increasing flood protection for the agricultural and residential areas to the east of the Park. The main users of the data are the Everglades Restoration Department and Planning Department of SFWMD (South Florida Water Management District).

Our findings are summarized below:

1. Management of water levels in the compartmentalized WCA's has enhanced interactions between surface water and ground water by establishing and maintaining water-level differences across levees that drive substantial underflow beneath the levee through the permeable limestone of the surficial aquifer. We know from published work that water fluxes are significant through the permeable bottoms of canals immediately adjacent to levees, but our results are some of the first to indicate significant fluxes through the less-permeable wetland peat. Although lower in magnitude than hydrologic fluxes through canal bottoms, vertical fluxes through peat are important because they occur over a much larger area of the wetlands, extending miles from the levee. For example, the relatively high water levels that are maintained in WCA-1 drive ground-water flow under the L-7 and Hillsboro levees and upward into the eastern part of the ENR and the northern part of WCA-2A, respectively. Downward flow occurs in central and western ENR, central and eastern WCA-2B, and central WCA-2A.

2. In addition to man's influence on interaction of surface water and ground water, another major control is the distribution of transmissive and restrictive zones for ground-water flow in the aquifer. A limestone layer near the top of the surficial aquifer is the main conduit that links recharge areas in WCA-1 with discharge areas in the ENR and WCA-2A. The transmissive limestone layer is located

between +10 and -30 feet NGVD (1929 National Geodetic Vertical Datum) and has horizontal hydraulic conductivities ranging between 150 cm/d (centimeters per day) in the denser parts of the limestone to greater than 6500 cm/d in well-indurated parts. Underlying the limestone is coarse sand to -70 feet NGVD grading to fine sand at the base of the surficial aquifer at -180 feet NGVD. Horizontal hydraulic conductivities in sands range from 30 cm/d in the fine sands to greater than 6,500 cm/d in the coarsest sands. At the top of the surficial aquifer is 2 to 4 feet of organic wetland sediment (peat) that acts as a hydraulically restricting layer that impedes vertical flow. The median estimate of vertical hydraulic conductivity of peat in northern Everglades sites was 17 cm/d, which is similar to that of a very fine sand, but lower by several orders of magnitude lower than hydraulic conductivities of the limestone and sand aquifer that underlies the peat.

3. Measured vertical fluxes through peat in the northern Everglades ranged from less than 0.04 cm/d (detection limit) to 10 cm/d, which, at the upper limit, is more than an order of magnitude higher than average daily precipitation or evapotranspiration (approximately 0.5 cm/d). Fluxes generally decreased with distance from levees toward central areas of the compartmentalized WCA's, where the direction and magnitude of vertical fluxes responds more to regional influences. The net, long-term interaction between ground water and surface water in the WCA's appears to be a small downward flux from surface water to ground water. The net downward flux is most likely a response to the long-term effect of storing water and maintaining relatively high water levels within the WCA's. Outside the Everglades, water levels have tended to decline over the past 50 to 80 years due to ground-water withdrawals and subsidence in some areas.

4. Vertical hydrologic fluxes between surface water and ground water were determined by direct measurements using seepage meters and indirect estimates based on modeling of vertical transport of chloride in peat. Neither measurement technique worked at all study sites. Seepage-meters were most reliable at sites where vertical hydraulic gradients in the peat were greater than 0.1. The average uncertainty of vertical flux estimates determined from replicate seepage-meter measurements was 50 percent. Modeling vertical transport of chloride in porewater to estimate hydrologic fluxes was generally a less reliable technique, due to difficulties in specifying fluctuations in chloride concentrations in surface water for the upper boundary condition. Currently we are quantifying the role of vertical hydrologic fluxes as sources and sinks for sulfate and mercury in WCA-2A and ENR, respectively.

5. Surface flow in Taylor Slough in the eastern part of Everglades National Park is augmented by surface water and shallow ground-water flowing southeasterly from the pine islands into Taylor Slough. Some of the southerly flow of water becomes ponded behind the Old Ingraham Highway, but there is clear evidence that at all times of the year a substantial amount of water flows beneath the highway through the porous road bed and aquifer, emerging in Taylor Slough. A historical canal usually referred to as the Rookery Canal also plays a role in distributing the shallow drainage across Taylor Slough. Environmental chemical tracers are being used to estimate the volumetric rate of ground-water inflow to Taylor Slough.

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Life History, Ecology, and Interactions of Everglades Crayfishes in Response to Hydrological Restoration

By Noble Hendrix, Jr.¹, William F. Loftus², and David Armstrong¹

The Everglades crayfish (*Procambarus alleni*) was first described by Hobbs (1942). *P. alleni* is found in a variety of Everglades fresh and brackish water habitats ranging from the short-hydroperiod Rocky Glades to perennially flooded sloughs, and from cypress forests to brackish mangrove swamps. The ubiquitous nature of *P. alleni* in South Florida wetlands demonstrates its ability to colonize and persist in very different habitat types and to play an important role in food webs within those environments. Because crayfish can assimilate detritus into biomass (Momot, 1984), they are efficient providers of energy to higher trophic levels should be considered. In Everglades National Park (ENP), many predators have been shown to consume *P. alleni*. The original proposal to study the Everglades crayfish (*Procambarus alleni*) was of limited scope and duration, and formed part of a Master's program for a student. The scope included the collection of density and biomass data for the crayfish across a hydrological gradient from the rocky glades into the Big Cypress Swamp, and the description of selected recruitment parameters for an ATLSS model. The most dramatic finding has been the discovery of a second species of crayfish, *Procambarus fallax*, in the study marshes. This species was previously known to range southward into Palm Beach County, but had never been identified from the Everglades. We are now studying the ecological interactions between the two species.

The purpose of this project is to provide empirical data in support of the ATLSS modeling program, which is the major tool used to measure ecological effects of proposed Everglades restoration activities. This study is providing needed estimates of crayfish abundance, size-frequency, fecundity, size at first reproduction, seasonality of gravid females, and the timing of movements and disappearance from the surface into burrows or solution holes as the habitats dry. Because two species of crayfish inhabit diverse surface environments throughout the Everglades region, we expect habitat partitioning to be expressed by behavioral or life-history adaptations in specific habitats, and to respond to ambient hydrological conditions. We have described characteristics of life-history and demographic to document adaptations to habitat type. This study has also provided the first, baseline database of the relative abundance and standing stocks of the two species in several habitat types from south Florida. This has been accomplished by obtaining seasonal abundance information in habitats spanning a hydrological gradient in Everglades National Park and Big Cypress National Preserve.

In the first segment of this study, we collected the first records for *Procambarus fallax* in south Florida wetlands. We amassed life-history data for the Everglades crayfish, *P. alleni*, as well as *P. fallax*, by collecting 790 throw-trap samples. We tested the throw-trap method for crayfish capture efficiency to estimate an average efficiency by location (based on data collected in July of 1997). The rates were Shark Slough spikerush 56 percent (± 15 percent) Shark Slough sawgrass 49 percent (± 24 percent), BICY domes 60 percent (± 13 percent), BICY prairie 59 percent (± 24 percent) and East Slough 75 percent (± 22 percent). We examined data collected by this project, and from archived samples back to 1985, to understand the habitat requirements (particularly hydrological requirements) of each species. Results of that effort included:

1. Indications of a strong link between species-specific requirements and hydrology: *P. fallax* inhabited long hydropattern locations while *P. fallax* inhabited short hydroperiod locations. The two species overlapped in areas that are intermediate in hydroperiod.

2. Species distributions at sites changed in relation to short-term changes in hydrology, then reversed when normal hydropatterns return.

We collected ovigerous *P. fallax* in sawgrass, spikerush and cypress domes; however, field observations suggested that the ovigerous females are using sawgrass habitat preferentially. Additionally, it appeared that newly detached crayfish are also found in higher numbers in sawgrass versus spikerush habitats. The lack of information on growth for either *P. fallax* or *P. alleni* led us to attempt to raise newly detached crayfish under laboratory conditions. While laboratory aquaria in no way simulated field conditions, molt increment has been reported to be somewhat stable irrespective of habitat. These molt increments in captivity averaged 0.94 mm/molt in *P. fallax* and 1.368 mm/molt in *P. alleni*.

Activities in 1999 are incorporating the following areas of study:

- Initiation of caged-crayfish experiments in the field in 1999. Through placement of individually marked animals in the field, we intend to simulate field growth rates without an extensive mark-recapture scheme.
- Collection of the two crayfish species, and potential prey items, for stable isotope analysis. The mastication process of crustaceans results in the gut contents being unrecognizable. Stable-isotope analysis, while not a quantitative method for assessing diet contents, has proven useful in assessing trophic links, placement, and food-web pathways.
- Determination of species-specific hydrology requirements through additional analysis of archived samples, including samples collected in 1996 and 1997 in Shark Slough, BICY, East Slough, Taylor Slough, and Conservation Area 3, and archived samples collected from 1975-1997 in ENP.
- Incorporate crayfish hydrology requirements into a spatially explicit coverage through ARC/INFO. Using existing coverages of water depth provided by ENP hydrologists, and field samples collected during the period matching the water depth coverages, we plan to create a species-distribution map. In 1999 we plan to ground-truth predicted distribution maps through field collections.
- Initiation of pilot study of mechanisms that are responsible for creating the patterns of species distribution. Using mesocosms, we will attempt to simulate various drying conditions, which might favor one species over another in microhabitats such as marsh, cypress prairie, and cypress domes. We will examine the survival of each species, its strategy for coping with falling water depths, and related factors.

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Geochronology and Metal Deposition in the South Florida Ecosystem

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Managing an ecosystem ideally requires a full knowledge of the environmental dynamics. If no historical environmental records exist, the employment of other methods is necessary to obtain this information. A well-known geochemical procedure that supplies time information is the use of short-lived isotope chronological methods. Of the many naturally occurring nuclides, ^{210}Pb was found to be the best suited for gauging the timing of environmental changes in Florida Bay and in the Everglades of South Florida. The age-depth relationships in cores were calculated using the ^{210}Pb method at 35 sites within Florida Bay and at 58 sites in the Everglades. In the Florida Bay system, ages were independently confirmed by comparing the distribution of the known concentrations of atmospherically anthropogenic total stable lead recorded in dated cores to similar data in an annually banded coral. In the Everglades system the ages were confirmed by photographic evidence that bracketed changes measured in the cores.

Cores from three sites in the central part of Florida Bay were selected for further analysis. X-radiographs revealed laminae over most of their length that indicated negligible sediment disturbance. The ^{210}Pb and ^{226}Ra were measured at 2-cm increments throughout these cores. Maximum activities of total ^{210}Pb were not much higher than ^{226}Ra activity. Thus, high-frequency measurements of radium were needed to construct accurate chronologies from excess ^{210}Pb (total ^{210}Pb minus ^{226}Ra). The ^{210}Pb profiles were nearly exponential, indicated evidence of little sediment mixing, and were consistent with a constant rate of delivery of excess ^{210}Pb and sediment mass. Mean accumulation rates ranging from 0.17 ± 0.02 to 0.92 ± 0.04 g/sq cm/yr (ca. 0.42 to 1.22 cm/yr) provided age-depth assignments to about 100 years BP.

Because ^{210}Pb dating is usually based on several plausible but untested assumptions, age-depth assignments generally must be validated by independent means. Fallout ^{137}Cs and stable lead profiles in the cores were compared with time records of atmospheric deposition at Miami (1964 maximum) and continental atmospheric lead concentrations (1972 maximum), respectively. For lead, profiles were also compared with lead/calcium ratios (1978 maximum) in annual coral bands from a specimen (*Montastrea annularis*) located on the Atlantic side of the Florida Keys (Shen and Boyle, 1987). Age-depth assignments in the cores were confirmed by the correlation of the ^{137}Cs peak as well as the nearly perfect match with the lead distribution in the coral (Robbins and others, 1998). The analysis of the cesium distribution also indicated that there is a time averaging of the distribution of metals in the bay of approximately 16 years. $^{239+240}\text{Pu}$ measurements confirmed this time averaging model (Robbins and others, 1998). This means that the system requires approximately 16 years to remove any metal that is introduced into it. Two cores were analyzed for mercury, barium, and uranium in addition to the lead. The barium and uranium concentrations vary, whereas a mercury maximum occurs in the cores around 1960.

Three cores were selected for metal analysis in the Everglades system. These cores are on a north-south traverse transecting an impacted area. High phosphorous concentration and the high growth rate of cattails distinguish the impacted area. Because of the high growth rate of the cattails and consequent increased production of peat at the surface, the concentration ^{210}Pb became diluted, resulting in declining profiles. However, at all sites the convergence of the ^{210}Pb and ^{226}Ra activities at depth demonstrate that an equilibrium level is clearly defined. This level is estimated to be the 100 ± 25 year horizon. The determination of the metal inventory above this horizon indicated that most

metals were deposited at a similar rate. One core taken outside of the impacted zone was dated. The distribution of metals in this core has a unique separation between normally coherent metals. Mercury, aluminum, and titanium are very coherently peaking around 1960 and around 1920, whereas copper, arsenic, cadmium and manganese show only a continuous increase through time. Lead peaks around the 1972 horizon, confirming the date as determined by the ^{210}Pb . The conclusion of this study is that short-lived isotopic chronologic methods are valuable in determining the history of metal deposition.

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Buttonwood Embankment, Northeastern Florida Bay

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The Buttonwood Embankment, a coastal levee averaging 1.5 ft in height, was first described as the “embankment that impounds the freshwater of the lower three counties of Florida” and separates the peninsula of Florida from Florida Bay (Craighead, 1964). Of the many questions concerning environmental change in Florida Bay two are: (1) What part does this “Coastal Levee” play in the hydrologic regime of southern Florida? and (2) Are rising sea-level or hydrologic management practices responsible for the environmental changes over the years? These questions were addressed in a recent study sponsored by the Everglades National Park in cooperation with the U.S. Geological Survey. A total of 32 cores was obtained: 6 on the embankment (a traverse along Taylor Creek and a traverse near Crocodile Point), 8 in the banks and basins of Florida Bay and 18 in the marsh/swamp. The chronology of events was established using short-lived isotopic chronological methods and the paleontological analysis.

Results of the chronological and paleontological analyses show that there have been long-term fluctuations related to sea-level changes during the last 2,000 years. There have also been significant changes noted during the last 50 years that can be attributed to hydrologic management of the water system of southern Florida.

Long term development: The nature of the long-term changes is best explained by climate variations that have taken place during the past 2,000 years. Two climatic events occurred within this timeframe, (1) the Medieval Warm period (800-1300 AD) and (2) the Little Ice age (1500-1800 AD). Each of these has left their signature on the vegetation of this part of South Florida (Willard and Holmes, 1999).

Concurrent with climate variability is sea-level change. Sea level in the Florida Bay area has been rising at ~ 3 mm per year for the past 150 years, as measured at Key West and Miami. There is a dichotomy of opinion on the nature of sea-level rise along the Florida Coast. Many investigators invoke a slow and continuous rise in sea-level (Scholl and others, 1966; Robbin, 1984), while others present evidence of step-type changes in sea level. The latter suggest that a higher sea level than present (~ 0.5 meters) occurred between 600-1000 years BP (Fairbridge, 1974; Stapor and others, 1991), the time of the Medieval warm period.

A conceptual model of bank formation consisting of six phases was constructed and tied to sea level variation over the past 2,000 years. In the initial phase, about 2,000 years ago, the region that is presently occupied by the embankment was a coastal freshwater pond. Peat and freshwater marl were deposited on the floor of the pond, which was separated from the marine environment by a coastal ridge and maintained a freshwater hydraulic head similar to the pre-1900 Everglades uplands. During the second phase, from about 2,000 to 1500 years ago, the coastal ridge was breached, and estuarine carbonate sediments were deposited in the pond. During the winter months, weather fronts stirred up the sediment in the adjacent bay. Some of the resultant turbid water was transported into the coastal ponds by tides. The coastal pond became a mixing zone of freshwater runoff from precipitation associated with the front and marine turbid tidal water, causing a shoaling of the pond. Similar to development of Lake One near Taylor Creek, this situation provided an opportunity for mangrove encroachment and resulted in mangrove peat being deposited over estuarine marl. Phase 4 was a

situation similar to the present one at Crocodile Point. The central ephemeral pond catches sediment filtered through the mangrove fringe. The trapped sediment was very fine, but contained terrestrial fauna that live on the short interior vegetation. Phase 5 was a continuation of this process that resulted in a relatively thick terrestrial deposit as evidenced by the meter-thick section containing terrestrial snails on the Taylor Creek traverse. This deposit has a date of approximately 1,000 years, which corresponds to the Medieval Warm period and the high stand as determined by Stapor and others (1991). The final phase included the lowering of sea level during the Little Ice age which exposed the fringe to erosion and elevated the region relative to sea level creating the embankment obvious today along the shoreline of the bay.

Short-term development: Through the past century there have been changes to the embankment caused by the “replumbing” of the South Florida drainage. Early changes are hinted at in apparent change in vegetative patterns, but the most significant changes recorded in the ecosystem took place during 1950-60. Because the bank was emergent during this time, there is no depositional record on it, but there were some significant alterations both land ward and seaward. In the bay, the building of the bank began between Pass Key and Lake Key. This infilling appears to have been completed in twenty years. Inland, in the vicinity of Taylor Creek, a lake was filled and much of the freshwater vegetation disappeared becoming a mangrove marsh.

Comparison of the long-term and short-term changes indicates significant differences. The sea-level rise during the Medieval Warm period and Little Ice Age, with the potential increase in saltwater influx, produced only slight changes to the vegetative patterns and there were no recognizable changes within Florida Bay. Even though the changes that have occurred since 1950 have taken place during rising sea level, these changes are far more extensive than those during previous high stand. This points to the hydrological management practices associated with the urban development are the major factors in these recent changes.

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Fish Recruitment, Growth and Habitat Use in Florida Bay: An Integrated Team Approach

By Donald Hoss¹, William Hettler¹, David Peters¹, Allyn Powell¹, Gordon Thayer¹, Lawrence Rosas², Michael B. Robblee³, Richard Matheson⁴ and David Camp⁴

Florida Bay is a complex of seagrass-dominated subtidal environments interrupted by numerous carbonate mud banks and mangrove islands. The Bay undergoes wide swings in environmental parameters, particularly salinity in the central and northeastern regions. Upstream water management activities in south Florida are generally assumed to have modified the quantity, timing and distribution of freshwater flow into Florida Bay by storing and diverting water for water supply and flood control purposes. This changed hydrology is thought to have contributed to a general marinification of the Bay and to have increased the frequency of occurrence and intensity of hypersaline conditions in the Bay. The implications of these changes to secondary production and nursery function are poorly understood. The goal of this project is to document benthic and larval community structure in relation to seagrass habitat and salinity in Florida Bay. The understanding developed here will be used to evaluate and predict the functional response of Florida Bay to upstream hydrologic modifications associated with restoration activities in south Florida.

Evidence is accumulating that changes in fish and invertebrate abundance and community structure at both the local scale (Robblee and DiDomenico, 1992; Sheridan and others, 1993; Thayer and others, 1993) and at the regional scale (Matheson and others, in press; Thayer and others, in press) have occurred in Florida Bay. These changes follow a period of seagrass habitat loss and a subsequent shift from a clear water system to one characterized by extensive and persistent algal and turbidity blooms. The role salinity has had in these community changes or in impacts to secondary production or nursery function is poorly understood. Modeling evidence suggests that salinity is of primary importance (Browder and others, in press).

This project was initiated in October of 1998. Quantitative collections characterizing the benthic and larval fish and invertebrate communities are being made at 18 stations (6 east, 6 central, 6 west) twice annually, in April at the end of the dry season and in October at the end of the wet season. At each station, five samples will be collected in two habitats, bank and basin. With each animal sample seagrass habitat will be characterized. Ideally, field collections will be made under both hypersaline and estuarine conditions in Florida Bay. The specific objectives of this project are: (1) to document fish and shrimp community structure along salinity gradients in Florida Bay; (2) to document fish and shrimp community structure along local depth and habitat gradients; (3) to evaluate the relationship between fish and shrimp abundance and seagrass micro-habitat; and (4) to evaluate recruitment in relation to seagrass habitat and salinity across the Bay.

This project is a joint project involving the National Marine Fisheries Service, the U.S. Geological Survey, and the Florida Marine Research Institute. Funding for this research is largely provided by the U.S. Department of Interior South Florida Ecosystem Restoration Program "Critical Ecosystem Studies Initiative;" and, in part, from the U.S. Geological Survey, Florida Caribbean Science Center for the Empirical and Modeling Studies in Support of Florida Bay Ecosystem Restoration Program.

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Temporal Salinity and Seagrass Changes in Biscayne Bay

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and Debra A. Willard¹

The objectives of the Ecosystem History of Biscayne Bay and Southeast Coast project are to: (1) assess the spatial variability in the distribution of modern biota (foraminifera, ostracodes, molluscs, diatoms, and palynomorphs) in Biscayne Bay; (2) determine how these distributions relate to the present environmental conditions (fresh water input, salinity, nutrient supply, seagrass, and contaminants) in the Bay; (3) interpret the temporal variability in the measured environmental conditions by applying modern biotic and environmental associations and geochemical data to biotic and geochemical data from downcore sediments; and (4) analyze the timing of environmental changes as determined by ²¹⁰Pb dated samples and relate the changes to historical events in South Florida.

This project is using faunal (foraminifera, ostracodes, and mollusks), floral (palynology and diatoms), and geochemical (stable isotopes and trace element geochemistry) data to examine the ecosystem history of Biscayne Bay and adjacent regions. Surface sediments collected from sites within Biscayne Bay and adjacent regions are being analyzed for their faunal and floral compositions. These data are correlated to water column data (temperature, salinity, pH, dissolved oxygen, nutrients, and redox potential) from each collection site and ground-water data (salinity, nutrient, stable isotope and trace element) collected at specific sites. Calcareous shells of living organisms are analyzed at Duke University for their trace element composition. In addition, the National Oceanic and Atmospheric Administration is currently gathering surficial sediment geochemistry data on samples collected near or at many of the ecosystem sites. Quantitative analyses of these data are used to determine controls on the modern faunal and floral distributions in the Bay. The data are also used to identify organisms that are useful environmental indicators, derive trace element (Mg/Ca ratio) calibration equations for modern bay salinities and temperatures, and determine the source areas for specific submarine ground-water flows into the Bay.

Distinct faunal distributions are identified within Biscayne Bay that are strongly associated with salinity, nutrient, and seagrass distributions. Trace element geochemical analyses of water and shells indicate a strong correlation between salinity and shell trace element geochemistry. Faunal distributions and shell geochemistry from sediment core samples, dated using ²¹⁰Pb, indicate significant environmental changes in Biscayne Bay over the past 150 years. The mid-1800's were characterized by low salinities and upper estuarine conditions. At the turn of the century, a significant faunal and floral shift occurred, indicative of higher salinity and lower estuarine to near marine conditions. This was accompanied by an increase in seagrass abundance. Bay waters became more saline (lower estuarine conditions) in the early 1900's. At about 1940, another faunal shift is evident suggesting a change to highly fluctuating annual salinity conditions with episodic periods of hypersaline conditions. Seagrass abundance remained persistent throughout this period. The most recent period (late 1980's to present) shows a slight decrease in relative annual salinity and reduced seagrass density. The carbon geochemical record from lower Biscayne Bay shows distinct periods of increased terrestrial charcoal sedimentation in the mid-1800's, at the turn of the century, and at about 1940. These events indicate increased charcoal production from fire events, giving us a proxy for burn frequency in southern Florida.

An understanding of pre-existing ecosystem conditions in Biscayne Bay and the evolution of the Bay is necessary to establish the range of natural variability and the impact of human influences in the region. The faunal and floral events detailed in Biscayne Bay show natural variability in salinity with a progressive increase in salinity throughout the last 150 years. This trend is punctuated by discrete events attributed to construction of the Flagler Railway, implementation of water management practices, and channelization of freshwater flow in South Florida. These results suggest that conditions within Biscayne Bay and adjacent regions during the past several decades may not represent the norm, and that significantly different salinity and seagrass conditions existed before intense water management practices and land development in southern Florida began. Restoration efforts need to reflect this possibility and incorporate this information into the present hydrologic and circulation models for Biscayne Bay and adjacent regions. This record reflects the importance of volume and rate of freshwater flow into Biscayne Bay and adjacent regions for the stability of the ecosystem and suggests an increase in freshwater inflow to maintain and improve the natural health of the Bay.

Results to date for this project have been provided to the Central and South Florida Restudy Project describing the impact of reduced freshwater flow to Biscayne Bay and surrounding regions. This project will establish methodologies for application to restoration of other Fragile Environments within our Nation. Spatial reconstructions of environmental conditions for the last 150 to 200 years will be used to produce synoptic maps of salinity, nutrient, and substrate conditions for Biscayne Bay. The data are compiled and can be accessed at <http://geology.er.usgs.gov/gmapeast/fla/home.html>, and a summary publication is being prepared on the ecosystem history of Biscayne Bay. These data are necessary for setting restoration objectives, supplying circulation modelers with control points to test their circulation models and modeling future outcomes of land and water management decisions, and locating sites at which restoration objectives can be monitored.

This project has benefited from collaboration with Biscayne National Park, Metro-Dade Department of Environmental Resources Management (Metro-Dade DERM), South Florida Water Management District (SFWMD), National Oceanic and Atmospheric Administration (NOAA), and Duke University.

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Tracing Food Web Relations and Fish Migratory Habits in the Everglades with Stable Isotope Techniques

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A main issue currently under investigation by a multi-agency taskforce in the Everglades is the cause of bioaccumulation of methylmercury (MeHg) up the food chain. A clear understanding of the aquatic food web is essential for determining the entry points and subsequent biomagnification pathways of contaminants. The traditional method of food web investigation focused on the determination of gut contents (literally, “who ate what”), and is still used today. More recently, stable carbon, nitrogen and sulfur isotope analyses of plants, invertebrates, and vertebrates have been used to establish relative trophic levels among various organisms because at each ascending trophic level, there is an increase in the carbon-13 (^{13}C) and nitrogen-15 (^{15}N) content of the organism due to selective metabolic loss of carbon-12 (^{12}C) and nitrogen-14 (^{14}N) during food assimilation. Thus, an organism is typically enriched in ^{13}C and ^{15}N relative to its diet by 1 to 3 parts-per-thousand (permil). There appears to be little or no enrichment in sulfur-34 (^{34}S) with increasing trophic level.

The nitrogen isotopic compositions ($\delta^{15}\text{N}$) of organisms in the Everglades range from -10 to +20 permil. These $\delta^{15}\text{N}$ values are in good agreement with suspected trophic position; primary producers have lower values than herbivores while omnivores and carnivores have successively higher values. Plants show an extremely large range of values. Most of the variability is in the macrophytes, and these almost always have lower values than algae. Among the invertebrates, insects show considerable overlap with crustaceans and small fish but generally have lower $\delta^{15}\text{N}$ values. Crustaceans have lower $\delta^{15}\text{N}$ values than most fish. Small omnivorous fish have lower $\delta^{15}\text{N}$ values than larger carnivorous fish. In general, the $\delta^{15}\text{N}$ values of gambusia (mosquitofish) are 7 to 9 permil higher than the values for co-existing periphyton mats. If bulk periphyton is an important component of the gambusia food chain, the gambusia values are equivalent to 2 to 3 trophic levels above the bulk periphyton.

The carbon isotopic compositions ($\delta^{13}\text{C}$) of organisms range from -40 to -15 permil. In general, the $\delta^{13}\text{C}$ values of algae, invertebrates, and fish show considerable variability with little or no consistent increase in $\delta^{13}\text{C}$ with increasing trophic level. Hence, bulk carbon isotopes are not very useful for determining trophic position. However, there is usually very good separation of the $\delta^{13}\text{C}$ values of macrophytes and algae; most macrophytes have higher $\delta^{13}\text{C}$ values than algae and other organisms. The generally high $\delta^{13}\text{C}$ values of the macrophytes are inconsistent with their being a major food source in most locations.

Few samples have been analyzed for sulfur isotopic compositions ($\delta^{34}\text{S}$) but the preliminary data show a range of +5 to +30 permil. There appears to be little or no increase in $\delta^{34}\text{S}$ with trophic level; instead, the main controls on the $\delta^{34}\text{S}$ appears to be source and extent of sulfate reduction. Areas where the decreases in sulfate concentrations over time are caused primarily by sulfate reduction, show large increases in the $\delta^{34}\text{S}$ of dissolved constituents. These isotopic patterns are then incorporated into the biomass.

In general, organisms collected in high-nutrient sites near the Everglades Agricultural Area (EAA) have higher $\delta^{15}\text{N}$ values than ones collected in more pristine areas to the south. Near the EAA, organisms in the canals generally have higher $\delta^{15}\text{N}$ values than samples from adjacent marshes, and the $\delta^{15}\text{N}$ values decrease with distance from the canals. This difference probably reflects a persistently higher value of the $\delta^{15}\text{N}$ of dissolved inorganic nitrogen (DIN) at the canal sites than at marsh sites. One likely explanation for this pattern is denitrification in anoxic waters and sediments in stagnant

parts of the canals, which would cause the $\delta^{15}\text{N}$ of the resultant DIN to increase. Marsh sites near canals show a much larger range of isotopic compositions than more pristine marsh sites because of the periodic influxes of eutrophic canal waters.

These values provide valuable clues about trophic relations among consumers. Different sites appear to have different food chains, and some show evidence for some seasonal differences in the importance of different food sources. At some sites (for example, U3 in Water Conservation Area (WCA) 2), the isotopic data suggest that algae is a major food source to local food webs. In contrast, at other sites (for example, cell 3 in the Everglades Nutrient Removal (ENR) area), decaying cattails (and the microbes that live on them) appear to be a major food source.

The compositions and spatial distributions of the carbon, nitrogen, and sulfur isotopes suggest that the values reflect spatial variability in reducing conditions in the marshes that favor methane production, sulfate reduction, and perhaps denitrification. The isotopic compositions of aquatic plants appear to integrate the variability in water-column isotopic compositions due to redox reactions and other factors in the ecosystem, and these same patterns are incorporated throughout the food chain. Therefore, zones frequently dominated by particular redox reactions may be labeled by the isotopic compositions of local organisms. Furthermore, organisms that live in zones where geochemical conditions are different may have distinctive isotopic compositions.

The “isotopic labeling” of different environments implies that isotopic techniques might be useful for determining whether fish migrate from canals to marshes in response to changes in hydrologic or nutrient conditions. Largemouth bass at some sites (for example, the ENR outlet, L-7, and a mid-marsh site in WCA 1) have narrow and distinctive ranges in isotopic compositions. These compositions suggest that the bass at the WCA 1 do not migrate in or out of L-7, and that L-7 and the ENR-cell 3 sites have significantly different environmental conditions. The larger and overlapping ranges in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values at sites in WCA 2 and 3 are consistent with movement of bass between canal and marsh sites, probably in response to fluctuations in water levels. These data indicate that for adjacent canal and marsh sites where the primary producers have distinguishable isotope compositions, the isotope compositions of fish can be used to determine whether the fish migrate in and out of the marshes in response to changes in water levels or food availability. Because MeHg concentrations are a function of local environmental conditions, these isotopic data should prove useful for determining where some populations of game fish are acquiring elevated levels of MeHg.

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Distribution and Transport Mechanisms of Mercury and Methylmercury in Peat of the Everglades Nutrient Removal Area

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Mercury (Hg) studies in Canada, Wisconsin, and the Florida Everglades have shown that some wetlands are net production areas of methylmercury (MeHg). Concerns over whether net production of methylmercury may also occur in constructed wetlands prompted studies of a constructed wetland in Florida as part of the Aquatic Cycling of Mercury in the Everglades (ACME) project funded by the U.S. Geological Survey and the South Florida Water Management District.

The Everglades Nutrient Removal (ENR) project is a 3,800 acre treatment wetland constructed in 1994 to reduce phosphorous levels in agricultural runoff before discharging to the Everglades. The ENR is situated along a ground-water gradient between the Loxahatchee Wildlife Refuge and the Everglades Agricultural Area. Its location on a ground-water gradient provides the opportunity to examine the influence of upward (site P12, on the east side of the ENR) and downward (site P5, on the west side of the ENR) advective ground-water fluxes, and diffusive fluxes (site ENR103, located in the middle of the ENR) on concentrations, partitioning, and transport of mercury species in wetland peat. Ground-water flux may affect several important Hg-cycling processes, including (1) adsorption and desorption of Hg and MeHg; (2) geochemical controls on mercury solubility; and (3) mercury methylation and demethylation by preventing accumulation of reaction byproducts. We hypothesize that observed mercury levels in ENR sediments will differ spatially and temporally between these sites primarily due spatial and temporal differences in advective hydrologic flux, and may be important to the ENR mercury mass balance in low rainfall periods.

Ultra-clean sampling techniques were used during all sample collection and laboratory procedures. Sampling was conducted in January, April, and July 1997, which span the range of hydrologic conditions generally observed in south Florida - low water levels in January and April, and high water levels in July. Surface water and porewater samples were analyzed for total mercury (Hg_T), MeHg, dissolved organic carbon (DOC), sulfide and ultra-violet light adsorbance. Surface water and porewater samples were pumped through a Teflon sampling line and filter holder, and filtered with ashed, quartz-fiber filters (nominal pore size 2 μm) to ensure comparability. Sediments were analyzed for Hg_T , MeHg, organic carbon, and bulk density.

The following is a brief summary of some of our preliminary results from the study. Total mercury levels in surface waters at all sites ranged between 1.14 and 5.23 ng/L during this study. For all three sampling periods, the diffusion-dominated site (ENR103) had the greatest difference between porewater and surface water Hg_T concentrations. The observed porewater/surface water ratio for Hg_T ranged from 3.4 to 5.8 at site ENR103, compared to similar ratios at the advection-dominated sites (P12 and P5) of 1.2 to 2.7 and 1.6 to 4.2, respectively. This difference is likely due to the influence advection enhanced transport of porewater Hg during low-water conditions. Similar differences in porewater/surface water concentration ratios were observed for DOC and sulfide.

Porewater MeHg concentrations were often below the detection limits due to limited sample volume size and analytical interference by high DOC and sulfide levels. However, we were able to calculate porewater MeHg concentrations based on partitioning coefficients, sediment concentration profiles, and sediment porosity. We used these values to estimate MeHg mass fluxes from ENR sediments.

Estimated methylmercury levels were highest in the top 5 cm of sediments at all sites, and concentrations declined rapidly with increasing sediment depth. Highest sediment MeHg concentrations were observed in January 1997 at site P12 (3.6 ng/g dry weight), coinciding with the higher surface water MeHg levels at this site during the same time period. Sediment MeHg concentrations at sites ENR103 and P5 were generally lower than site P12, reaching a maximum concentration of 1.7 ng/g during July 1997 at both sites. Temporal differences in sediment MeHg levels are hypothesized to be related to spatial differences in ground-water-flux rates. Most of the MeHg values reported here are higher than those reported previously, which may reflect conditions associated with maturation of the ENR wetland or annual variability in water chemistry and methylation rates.

In summary, we observed spatial and temporal variability in the surface waters, porewaters, and sediments of the ENR across a hydrologic gradient. These variations are hypothesized to be controlled by systematic changes in ground-water/surface water interactions along this hydrologic gradient. It is likely that the hydrologic settings are influencing Hg and MeHg sources and sinks in the ENR.

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Parameterizing Individually Based Models of the Snail Kite

By Wiley Kitchens¹

The snail kite (*Rostrhamus sociabilis*) is a small endangered raptor whose distribution in the United States is limited to the freshwater wetlands of southern and central Florida. The snail kite integrates over the entirety of the system's freshwater complex and is entirely dependent upon its aquatic resources for its existence. Because of its endangered status and dependence on the hydrologic restoration of the system, individual-based models of the dynamics of the snail kite population have been determined to be critical for assessing the success of restoration.

Earlier restoration attempts were seriously impaired over conflicting concerns regarding alternatives being considered at that time and the recovery of snail kites. The concern generated considerable support for empirical studies of dispersal and demographics of the snail kite population in South Florida. This work provides support for parameterizing the individually-based snail kite model being developed for the Across Trophic Level System Simulation model (ATLSS) being developed to assess hydrologic alternatives in the Restoration of the South Florida Ecosystem initiative. The model will concentrate on demographic and behavioral details. The proposed effort will include bio-energetic details and life-functions of individual kites evaluated on a daily time scale capable of determining the population viability of the kites over the history of the proposed restoration.

These models will provide a means of testing our hypothesis that the population responses of the kites are principally behavioral (for example, migration) for drought events of low intensity and spatial extent, but numerical (for example, changes in survival and/or reproduction) as severity and extent increase. These responses are tied integrally to the availability of the kites' forage base, the apple snail. The kites feed almost exclusively on the apple snails and are subject to the same environmental factors that influence the snails. Apple snails occur in areas of longer hydroperiods and their availability is severely reduced during drought periods.

Detailed studies on the demography and movement patterns of the kites (Bennetts and Kitchens, 1997) based on radio-telemetry and mark-resighting of banded birds, are being utilized to parameterize earlier crude models. These upgraded models will be used to estimate demography with emphasis on survival to evaluate influences of hydrologic conditions. The models will evaluate movement patterns including environmental conditions correlated with movements.

The work is currently contributing to the development of earlier an overly simple preliminary models developed within the OSIRIS framework (a modeling platform developed by Dr. Wolf Mooij of the Netherlands Institute of Ecology) into legitimately parameterized individual-based spatially explicit ATLSS models. These models will include behavioral and demographic detail and be capable of testing scenarios of hydrologic responses to manipulations of water deliveries and staging in the major wetland complexes of South Florida.

The project has been identified as a specific information need in the South Florida Ecosystem Restoration: Information Needs document prepared by the Science Subgroup of the Restoration Task Force. The proposed study provides an opportunity to quantify those impacts of hydrologic manipulations on the viability of the endangered snail kite. The critical habitat of this species, principally the Water Conservation Area landscapes and Lake Okeechobee, have been fragmented and manipulated for the last 50 years. This study should provide salient information to restoration managers for assessing restoration scenarios, particularly those that attempt to re-establish the dynamic gradient of the system and the attendant sheet flow.

Given the precarious situation of the snail kite in the United States, where it is confined solely to the South Florida ecosystem, and the fact that the species is wholly dependent on the critical functioning of the wetlands within this system for its survival, it is imperative that the model that will be used be based on absolutely sound scientific information, which can only be provided by this project.

Funding for this research was provided in significant part from the U.S. Department of the Interior South Florida Ecosystem Restoration Program “Critical Ecosystems Studies Initiative” (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the “Atlas Tropic Level System Simulation” was also provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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The Aquatic Cycling of Mercury in the Everglades (ACME) Project: A Process-Based Investigation of Mercury Biogeochemistry in a Complex Environmental Setting

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The Aquatic Cycling of Mercury in the Everglades (ACME) project was initiated in 1995 to provide a better understanding of the factors resulting in high mercury (Hg) levels in resident wildlife of the Florida Everglades. The overall objective of the ACME project was to examine in detail the biogeochemical processes that control mercury cycling in the Everglades, with particular emphasis on the mercury methylation and bioaccumulation. Ultimately, our intent is to integrate all our findings through the use of a variety of models so that potential effects of various ecosystem restoration alternatives on mercury toxicity can be tested.

To date, the ACME project has provided many new insights into the processes controlling mercury cycling in the Everglades, as well as a better general understanding of biogeochemical processes operating in wetlands. Surface water Hg concentrations are low (total Hg concentrations generally less than 5 nanograms per liter), and are variable both spatially and temporally. At the ecosystem scale, seasonal variations in total Hg concentrations in surface water appear to be primarily controlled by rainfall, the dominant source of Hg to the Everglades, although there is significant variability in these seasonal trends. There are no apparent spatial trends in total Hg in surface water, suggesting that atmospheric-Hg deposition of is randomly distributed.

Methylmercury (MeHg) in surface water shows a general trend toward increasing concentrations from north to south, with maximal concentrations observed in southern Water Conservation Area (WCA) 2 and central WCA 3. Seasonally, MeHg concentrations are generally highest in the summer, when deeper water levels and warmer conditions exist. These trends in MeHg concentrations are in agreement with the MeHg concentrations observed in sediments, and measured rates of microbial methylation. At any particular location, Hg methylation rates were found to be greatest in southern Water Conservation Area (WCA) 2 and central WCA 3, and the site of greatest methylation activity was the surficial sediments. Microbial mercury demethylation is also occurring in Everglades peat, but unlike methylation estimates, demethylation rates showed no strong spatial trends. The primary Hg methylating agents were determined to be sulfate reducing bacteria, which emphasizes the need to examine sulfur cycling in parallel with mercury cycling studies. Excess sulfate is currently being delivered to the Everglades, and probably originates from agricultural runoff in the northern part of the system. Studies of dated cores from WCA 2A show that the influx of excess sulfur began in the early part of this century, concomitant with an influx of excess phosphorus. The excess sulfate stimulates bacterial sulfate reduction over large areas of the northern Everglades, and has a significant but complex relation to the extent and distribution of MeHg in the ecosystem.

Fourteen diel studies conducted from 1995 to 1998 demonstrated the importance of short-term changes in redox gradients that control the speciation and fluxes of Hg from the sediments to the water column, and from the water column to the atmosphere. In addition, close-interval sampling (centimeter scale) conducted during the diel studies documented the existence of strong chemical

gradients originating from the near-surface sediments, and are the primary transport mechanism of MeHg to the water column. Photochemical reduction and demethylation reactions both occur on a diel basis in the Everglades, and appear to be regulated by dissolved organic carbon, which limits light penetration into the water column. Mass-balance calculations show that most of the seasonal variability in MeHg concentrations in the water column can be accounted for by the estimated efflux rates from sediments and the photochemical demethylation rates in the water column.

Accumulation of MeHg in biota follows the same general trends observed for water-column MeHg concentrations and methylation rates, however, seasonal variability can be significant. Examination of gut contents of *Gambusia* (the dominant forage fish in the Everglades) showed that zooplankton are an important dietary component. This observation was in contrast to observations made early in the project, however, when very few zooplankton were found in the water column. Biota sampling on a diel basis showed that zooplankton are only present in the water column at night, and hide from predators during the day.

The ACME project has demonstrated the dynamic nature of the mercury cycle in the Everglades, and similar processes are likely operating in wetlands elsewhere. The existence of transient chemical gradients appears to be the key to understanding the complex relations between this atmospheric derived pollutant, rapid biogeochemical cycling and efficient bioaccumulation.

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The Sun's Detoxifying Effects on Mercury in the Everglades

By David P. Krabbenhoft¹ and James P. Hurley^{2,3}

Mercury (Hg) is a globally distributed contaminant that is currently impairing wildlife in many lakes, streams, and wetlands. The effectiveness of current methods to reduce Hg toxicity (emissions reductions, consumption advisories, and ecosystem management alternatives) in any ecosystem is predicated on having a good understanding of those factors that control Hg cycling in the environment. Photochemical reactions have long been known to affect the phase, redox state, partitioning, transport, and fate of many metals in aquatic environments. Probably no metal is more affected by exposure to sunlight (photosensitivity) in terms of its environmental behavior than Hg. Sunlight drives two important photochemical processes involving mercury: photochemical reduction and photochemical demethylation. Photochemical Hg reduction involves both redox and phase changes, from ionic Hg (II) to dissolved gaseous Hg (0). Dissolved gaseous mercury (DGM) is sparingly soluble in water, and will seek to evade from the water to the atmosphere, thereby removing Hg from the aquatic environment. Methylmercury (MeHg), the most bioaccumulative form of Hg, is also photosensitive and can undergo photochemical degradation to Hg (II), and then possibly reduced to DGM. This two step process serves two important roles, demethylation of MeHg to a less toxic form of Hg, and then possibly elimination of Hg from the aquatic ecosystem by evasion.

The Aquatic Cycling of Mercury of the Everglades (ACME) project has been investigating the role of photochemistry in the mercury cycle of the Everglades, and what environmental factors control these reactions. Results to date have shown that DGM production and evasion, re-oxidation of Hg (0), and MeHg degradation are all occurring in the Everglades. The quantity and quality of dissolved organic carbon (DOC) plays a major role in regulating the rates and locations of these processes within the water column of the Everglades. Dissolved organic carbon serves as an effective filter of ultraviolet light (the most important wavelengths for these photochemical reactions) and can substantially limit the water depths and yield rates of many photosensitive reactions. On the other hand, the interactions of DOC with incident sunlight results in the production of several chemical oxidants, which can drive the reverse reaction and re-oxidize DGM to Hg (II). This ionic form of mercury could then become methylated if transported to a methylation site (for example, the sediment-water interface).

Field and laboratory data from samples collected across the Everglades shows there is a systematic increasing trend from north to south in gross DGM production rates, ranging from about 0.1 to 1 ng per liter per day. A corresponding north-to-south decreasing trend in DOC concentrations is believed to be the primary controlling factor of the DGM production rates. At lower DOC levels, DGM production and potential mercury removal to volatilization is maximized. The southern most sites in Water Conservation Area 3 and Everglades National Park showed the highest gross DGM production rates, which were similar in magnitude to rates of Hg deposition from rainfall. Measured net DGM production rates (gross DGM production minus DGM oxidation) also show a strong north-to-south trend. Net DGM production rates are significantly less than gross production rates, and across all our sampling sites an average of only about 15 percent of gross DGM produced is available for volatilization.

Methylmercury degradation rates also show a strong north-to-south increasing trend in the Everglades (ranging from 2 to 15 percent per day), and are also thought to be controlled by light penetration limitations of DOC. Maximal photodemethylation rates measured in Everglades National

Park may be a principal reason why MeHg levels are not higher in resident aquatic biota. These rates of demethylation rival or exceed the microbial demethylation rates measured in sediments, emphasizing the need to consider this detoxification pathway when investigating Hg cycling processes. Current Everglades restoration decisions regarding water flow rates, sources, and depths will all have affects on the concentrations of DOC throughout this ecosystem, and will likewise have an affect on the photochemical processes that influence mercury toxicity in this sensitive environment.

Because the same set of mercury cycling processes operate in most aquatic ecosystems, our findings have applicability beyond the Everglades. In many aquatic environments, photochemical processes may be the most effective Hg detoxification mechanisms available to reduce the impacts of MeHg on local food webs (including humans). Strategies for managing aquatic ecosystems need to consider how management actions will influence factors important for photochemical reactions, and in turn, how these changes might affect Hg toxicity.

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Ground-Water Flows to Biscayne Bay

By Christian D. Langevin¹

Large quantities of fresh ground water were discharged to Biscayne Bay prior to the 20th century. There are several historical accounts of ships that replenished their potable water supplies by drawing freshwater directly from Biscayne Bay. Beginning in the early 1900's, an extensive network of drainage canals was constructed in southeastern Florida to lower the water table, reduce flooding, and increase the available land for agriculture and building development. These canals significantly altered the hydrology of southeastern Florida, lowering the water table and thus reducing ground-water discharge to Biscayne Bay. The current water-table altitude and gradient are not high enough to discharge large quantities of ground water into Biscayne Bay.

The flow of freshwater into Biscayne Bay is vital to the health of the estuarine ecosystem. In addition to the freshwater quantity, the timing of the freshwater input also is important. Prior to canal development, Biscayne Bay would have received most of its freshwater as discharge from upward ground-water flow through bottom sediments. These ground-water discharges to the bay are believed to have been relatively constant throughout the year, only fluctuating with the water-table head. In contrast, much of the current freshwater flow to Biscayne Bay occurs as pulse events of surface-water discharge at coastal canal structures, with most of the discharge occurring during the wet season (June to October). In 1995, 80 percent of the total canal flow to Biscayne Bay occurred during the wet season.

Water managers in southern Florida currently are evaluating alternative strategies for managing water resources. Some of these strategies involve changes to the canal operations that would route more water to Everglades National Park. In April 1996, the U.S. Geological Survey began a study to characterize the Biscayne aquifer near the Biscayne Bay western shoreline, quantify ground-water discharge to Biscayne Bay, and develop scientific tools that can be used to evaluate how changes in water-management scenarios would affect the ground-water discharge to Biscayne Bay.

Monitoring wells were installed in the Biscayne aquifer to help characterize the hydrogeology at the coast. These wells were installed in transects perpendicular to shore at three different locations: Coconut Grove, Cutler Ridge, and Mowry Canal. Each transect has nested well clusters both onshore and offshore. Cores were collected during the drilling of each well. The collection of water-level and salinity data from these wells began in March 1998. The data are being used to characterize the shape and position of the freshwater-saltwater interface and calibrate numerical models of ground-water flow.

Reliable and accurate methods for the direct measurement of ground-water discharge to Biscayne Bay do not exist. For this reason, variable-density, numerical flow models, which represent ground-water flow and the transport of salt, are being developed at two different scales. First, a regional three-dimensional flow and transport model will be used to simulate the flow of ground water toward the coast. This model will cover most of Miami-Dade County with a finite-difference grid, aligned parallel to the coast and a constant cell size both horizontally and vertically. The model will be used to simulate the regional flow of ground water toward Biscayne Bay during 1997 and 1998 and will be calibrated to measured water levels, canal flows, and salinity patterns using a monthly or weekly time step. Although this model will simulate variable-density ground-water flow, the resolution of the model grid cells will not be detailed enough to adequately characterize the freshwater-saltwater interface and ground-water discharge to Biscayne Bay. Instead, results from the model will be used to define the inland boundary conditions for three high-resolution, cross-sectional models.

A two-dimensional, vertical, cross-sectional model will be developed for each of three transects where water-level and salinity data are being collected. The purpose of the cross-sectional models is to quantify the discharge to Biscayne Bay by calibrating the models to water-level and salinity data. As ground-water discharge is expected to vary over tens of meters, these models will have a 10 x 1-meter-cell size in the x and z directions, respectively. Tidal effects will be simulated by changing the water level at the bay boundary during hourly or quarter-hourly time steps. Simulations will represent the period of time that data were collected in the field. Results from these models will be presented as ground-water discharge and salinity of the discharge as functions of time and distance from the shore. These discharge results will allow water managers to determine the effects of varying inland conditions on the distribution and timing of fresh ground-water discharge to Biscayne Bay.

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Field Measurement of Flow Resistance in the Florida Everglades

By Jonathan K. Lee¹ and Virginia Carter¹

Standing vegetation and bottom litter in the Florida Everglades create resistance (drag and shear) forces that slow the movement of water southward from Lake Okeechobee to Florida Bay. Gravity (represented as ground-surface slope), flow resistance, and wind, together with boundary inflows and outflows (at sloughs, creeks, and manmade structures) and areal inflows and outflows (of ground water, precipitation, and evapotranspiration), determine the depth and velocity of the water. Better representation of vegetative effects on flow resistance, in terms of parameters that describe the flow and vegetation, and better quantification of the parameters that appear in the resulting mathematical expressions are needed to improve numerical models of surface-water flow. Parameters that describe the flow and vegetation include flow velocity through the vegetation; water depth; slope of the water surface; and type, geometric characteristics, and density of the vegetation. Surface-water models with improved representation of vegetative effects on flow resistance, together with field measurements of flow resistance, can be used to study, for example, how changes in vegetative density affect changes in flow patterns.

Indoor flume measurements were made to identify the most appropriate mathematical expressions and parameters for representing flow resistance due to nearly homogeneous stands of sawgrass, one of the most common plants of the Everglades. Field measurements were made in April and November 1996 in the Shark River Slough and in September and November 1997 and July 1998 in Taylor Slough to obtain information on the relation between flow and vegetation characteristics. In this synopsis, we focus on the methods used to measure hydraulic parameters in the field and on preliminary results of the field measurements. Preliminary results from the indoor flume measurements were reported in Lee and Carter (1997).

During the field work, approximately 75 concurrent hydraulic and vegetation measurements were made in plant communities through which measurable surface-water flows were observed. Measurements of flow depths, flow velocities, and water-surface slopes were made to evaluate flow resistance. Vegetation sampling and analysis are discussed by Carter and others (1999) in this volume. During the 1996 measurements, the distance from the water surface to the firm bottom and the thickness of the litter layer were measured at each measurement site. An acoustic Doppler velocimeter (ADV) equipped with a down-looking probe was used to measure flow velocities that were commonly less than 1 cm/s. The ADV is a point-velocity-measurement device having a sampling volume smaller than 1 cm³. During the 1996 field measurements, two vertical velocity profiles were obtained at 5-cm increments of depth in the water column at each measurement site. Profile velocities collected in November 1996 were referenced to east, north, and up directions. Velocities were sampled at each measurement point in the water column for approximately 2 min at a frequency of five samples per second. These data were later filtered to remove erroneous samples. Points at which average correlations did not exceed 70 percent were not used in subsequent analyses. Mean velocities in the east, north, and up directions were obtained from the last 300 good samples (1 min of data) at each measurement increment. A spreadsheet was developed and used to integrate numerically each velocity profile between the top of the litter layer and the water surface. The mean horizontal flow speed and direction were also calculated in the spreadsheet.

A unique pipe manometer was developed and used to determine local water-surface slopes that are on the order of 1 cm/km. During the November 1996 field efforts, a 2.4-m-long, 7.6-cm-diameter plastic pipe with a short elbow at one end was positioned horizontally about 10 cm below the water surface and parallel to the flow direction with the elbow at the upstream end and pointing down. The centerline flow velocity in the pipe was measured by inserting an ADV, equipped with a side-looking probe, into the downstream end of the pipe. The velocity of water in the pipe is a function of the characteristics of the pipe and the difference in water-surface elevation at the entrance and exit. The pipe manometer was calibrated in a series of measurements in the U.S. Geological Survey tilting flume at Stennis Space Center, Mississippi. During the November 1996 field efforts, the manometer was used to make between one and four water-surface-slope measurements at each measurement site.

Fifteen complete sets of hydraulic and vegetation data were obtained during November 1996 field work at sites NESRS3 and P33 in upper Shark River Slough. The vegetation classes sampled were sparse rushes, medium rushes, medium sawgrass, medium mixed rushes and sawgrass, dense sawgrass, dense cattails, and very dense sawgrass. The distance from the water surface to the top of the litter layer ranged from 0.28 to 0.48 m, and the vertically averaged velocity ranged from 0.21 to 1.22 cm/s. The Manning's *n* coefficient, an empirical expression commonly used to express flow resistance in open channels, was computed for each measurement site. An approximate inverse relation between Manning's *n* and velocity was found. This is consistent with results obtained in flume studies (Lee and Carter, 1997). The limited data do not yet reveal a relation between vegetation type or density and the value of Manning's *n*.

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Synopsis of Flows and Nutrient Fluxes to the Southwest Coast of Everglades National Park, Florida, 1996-99

By Victor A. Levesque¹

The mangrove estuaries along the southwest coast of Everglades National Park (ENP) are dependent on receiving adequate freshwater and optimal nutrient concentrations to minimize adverse impacts to the habitat they provide for many organisms. The mangrove swamps and estuaries seem far removed from the land and water use practices of urban and agricultural areas of south Florida. However, land use, water use, and flood control practices in south Florida have altered the amount and timing of water flows that reach the estuaries on the southwest coast of ENP. As an element of the U.S. Geological Survey South Florida Ecosystem Program, a study was initiated to describe hydrodynamic characteristics and quantify water flows and nutrient fluxes of selected estuarine streams that receive water from the Shark Slough drainage area. These data are needed for hydrologic system models under development by local and federal agencies to be used for evaluating ecosystem restoration impacts.

The Broad, Harney, and Shark Rivers receive flows from the Shark Slough and were established as monitoring stations in 1996 for determining water flows and nutrient fluxes. Monitoring stations at Lostmans Creek and North River were added in 1999. Stations are equipped to record water velocity, water level, specific conductance, and water temperature at 15 minute intervals. Water velocities are measured using upward-looking acoustic Doppler current sensors. Water levels are measured using vented pressure transducers. Specific conductances near the surface and near the bottom of the water column are measured using four-electrode conductance sensors, and water temperatures are measured using integral thermistors in the conductance sensors.

Stations are visited every 4 to 6 weeks for sensor calibrations, stream discharge measurements, water-quality sample collection, and data retrieval from the data logger. Stream discharge measurements at the Broad, Harney, and Shark Rivers began in February 1997 and will begin in May 1999 at the Lostmans Creek and North River stations. Discharge measurements are made using a boat-mounted acoustic Doppler current profiler. Water-quality sampling began in February 1997 at the Broad, Harney, and Shark Rivers and will begin in May 1999 at the Lostmans Creek and North River stations. Water-quality samples are collected using a modified equal-width-increment method. Top, middle, and bottom temperature, specific conductance, pH, and dissolved oxygen are measured using a submersible multiparameter sensor during water-quality sample collection. The water samples are analyzed for total and dissolved nitrogen and phosphorus concentrations and specific conductance by the USGS water-quality laboratory in Ocala, Florida.

The streams are affected by mixed tides (semidiurnal and diurnal) that cause the flows to reverse direction one to two times per day. The instantaneous discharges show a long-duration ebb flow (toward the Gulf of Mexico) and a greater magnitude, but shorter duration flood flow (away from the Gulf of Mexico). Instantaneous discharge magnitudes are similar for the Harney and Shark Rivers and have ranged from approximately -8,000 to +8,000 ft³/s, whereas the instantaneous discharge magnitudes for the Broad River are less and have ranged from approximately -2,000 to +2,000 ft³/s. Tidal effects on the instantaneous discharge data are removed using a low-pass filter that attenuates the tidal signals that are less than about 30 hours in duration. The filtered data are used to estimate the residual flows.

Preliminary analyses of the residual flow data show seasonal and short-term variations. The Harney and Shark Rivers data show that larger pulses of residual flow (approximately 2,000 ft³/s) occur during the wet season and for shorter periods in response to severe storm events. Smaller pulses of residual flow (less than 500 ft³/s) occur in response to lesser storm events, and fluctuations near 0 ft³/s occur during drier periods. The Broad River residual flow data are about half the magnitude of the Harney and Shark Rivers and show the same pattern of fluctuations.

Water-quality data for the Broad, Harney, and Shark Rivers show significant relations between nutrients and specific conductance and that the majority of nitrogen and phosphorus occurs in a dissolved form. The Harney and Shark Rivers dissolved nitrogen concentrations are inversely related with specific conductance (significance level 0.02), and may indicate that the majority of dissolved nitrogen is transported from the upgradient areas to the estuarine rivers as fresher water flows into these streams. In contrast, the Broad River total and dissolved nitrogen concentrations are directly related with specific conductance (significance level 0.01) and may indicate that the higher concentrations are transported from the waters in the Gulf of Mexico to the river estuary. Total and dissolved phosphorus concentrations for all three rivers are directly related with specific conductance (significance level 0.02) and may indicate that the rivers are receiving higher concentrations of phosphorus from the Gulf of Mexico than from upgradient areas.

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Nutrient Analysis and Water-Quality Trends at Selected Sites in Southern Florida

By A.C. Lietz¹

Near the beginning of the 20th century, modifications to the natural hydrologic system of southern Florida, including the Everglades, were undertaken to furnish the urban and agricultural demands of an expanding population. These changes have evolved into an extensive system of canals, levees, pump stations, gated control structures, and water-conservations areas used for the drainage of wetlands, flood control, ground-water replenishment, and the prevention of saltwater intrusion. These modifications to the natural hydrologic system of southern Florida have resulted in the alteration of historical hydropatterns, especially as they relate to the Everglades.

A vital component in ecosystem restoration is the understanding of preresoration water quality. Because of an expanding population along the southeastern coast of Florida, the health of Biscayne Bay has been threatened by nutrient-laden discharges from the east coast canals, resulting from increased urbanization and agricultural practices. Plans call for extensive changes to the current water-management system to restore natural flow patterns into Everglades National Park. These changes--including the filling of canals, removal of levees, and rechannelization of canal discharges to Biscayne Bay--potentially could affect the fragile Biscayne Bay ecosystem. The U.S. Geological Survey conducted a study designed to understand nutrient concentration and distribution within the east coast canal system, compare sampling methods to determine which methods adequately represent stream cross-section water quality, and develop models for the estimation of nutrient loads from the canals to Biscayne Bay. Data were collected during the 1996 and 1997 water years with a report prepared during the 1998 water year.

Major findings from the project are as follows:

- Based on land uses in the Biscayne Bay watershed, median concentrations of total nitrite plus nitrate tended to be higher in agricultural areas than in urban or wetland areas. Median concentrations of ammonia, total phosphorus, and orthophosphate tended to be higher in urban areas than in wetland or agricultural areas, and median total organic nitrogen concentrations generally were higher in wetland and urban areas than in agricultural areas.
- Based on statistical comparisons using the Wilcoxon signed rank test, comparison of grab samples collected at 1.0-meter depth from the middle of the stream with depth-integrated samples collected by the equal-width-increment method showed no statistically significant differences between the two samples for total nitrogen, whereas 25 percent of the sites demonstrated differences between the two samples for total phosphorus. This would indicate that grab samples collected historically from 1.0 meter below the surface may be representative of total nitrogen concentrations, but not for total phosphorus. No significant differences were detected between grab samples collected from 0.5-meter depth and 1.0-meter depth for total nitrogen or total phosphorus. No significant differences were detected among samples collected from 0.5-meter depth and depth-integrated samples for total nitrogen; however, about 33 percent of the sample comparisons between grab samples collected at 0.5-meter depth and depth-integrated samples showed statistically significant differences for total phosphorus.

- Comparison of grab samples with depth-integrated samples using the line of organic correlation showed that grab samples tend to underestimate total phosphorus concentrations. This probably was the result of less suspended material being “captured” by a grab sample as compared to that from a depth-integrated sample.
- Nutrient models for estimation of loads were developed using the techniques of ordinary least squares regression based on the relation between load and discharge. Models developed for estimating total nitrogen loads had coefficients of determination (R^2) that averaged 0.86, and coefficients of determination for models developed for estimating total phosphorus loads averaged 0.72, indicating that 86 percent of the variation in the nitrogen load and 72 percent of the variation in the phosphorus load is explained by the discharge.

In an attempt to understand current and historical water quality, long-term trends in water quality from two surface-water sites potentially affected by the restoration effort, Miami Canal (S-26) and Tamiami Canal - Forty-Mile Bend to Monroe, currently are being investigated. Miami Canal is one of the principal canals that discharges to Biscayne Bay, and the Tamiami Canal site represents flow from the Big Cypress National Preserve to Everglades National Park. Extraneous variation in water-quality data can occur due to both seasonality and discharge. The specific statistical approach undertaken in this study involves compensating for the effects of seasonality and discharge. The application of the Seasonal Kendall Trend Test on residuals from concentration/discharge relations developed from the use of ordinary least squares regression techniques or on unadjusted concentrations was used in the study. This approach removes extraneous variation in the data so that specific anthropogenic processes that have occurred and have affected water quality over time are not “masked” and can be discerned. Trends at the two sites will serve as indicators of both improvement or deterioration in water quality with time.

Study results will identify statistically significant trends and provide quantitative information as to the rate of change in specific constituents over time. Information gained from this study will provide water managers and planners with a better understanding of current water-quality conditions prior to the initiation of restoration efforts and also an understanding of the interdependence of Biscayne Bay and the Everglades ecosystems. Additionally, the information will provide a valuable resource for comparison of preresoration and postrestoration water quality as well as a means of determining the effectiveness of restoration efforts in enhancing water quality in the Everglades and Biscayne Bay ecosystems.

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Everglades Aquatic Ecology Studies

By William F. Loftus¹

These multiple research projects are planned to provide data on the structure and functioning of aquatic animal communities to help guide Everglades restoration. Some of the work has been a long-term effort funded originally by the National Park Service (NPS), then partially transferred to the U.S. Geological Survey (USGS). NPS has retained responsibility for continuing the long-term monitoring program for aquatic animals in the southern Everglades, whereas USGS has had the role of collaborating to analyze and publish the data sets. Although the information contained in those data bases is considerable and valuable, much work remains to be done to understand aquatic system ecology in south Florida wetlands.

The absence of historical data on the ecological structure and functioning of the mosaic of wetlands that comprised the predrainage Everglades makes it difficult to agree upon restoration targets. Despite the research conducted in the past decades, there remain vast gaps in understanding the structure and dynamics of biotic communities in response to system hydrology, disturbances, and interactions with the landscape. Specifically missing are the empirical studies that provide data on the distributions and dynamics of primary producers such as periphyton and vascular vegetation in response to hydrology and season, and their subsequent translation into invertebrates and small fishes that are the prey for wading birds and other consumers. The loss of large areas of specific wetland types, for example the short-hydroperiod wetlands, is thought to have resulted in the biotic degradation of the entire system, but the mechanisms involved in that degradation have not been well studied. To acquire information about the spatial extent of the specific areas that ought to be targeted for acquisition, it is necessary to document the ecology, life history parameters, and the functional responses of the biota under a variety of present-day hydrologic regimes. It is also important to test hypotheses on biotic interactions, and about biological responses to landscape conditions, experimentally.

This series of projects intends to develop empirical, long-term data bases required to understand critical ecological processes, and to provide scientifically credible data to important modeling efforts such as “Across Trophic Level System Simulation” (ATLSS) model. The studies include investigations of the factors regulating spatial relationships among habitats and biota, the effects of disturbances (fires, freezes, hurricanes, droughts, and floods) on ecological processes and a description of trophic interactions and food webs across the landscape. Major topics of investigation at this time include the inventory and monitoring of the native and introduced freshwater fishes, reptiles, and amphibians of southern Florida, including such potentially threatening animals as the Asian swamp eel. We are analyzing the long-term dynamics of freshwater fishes, macroinvertebrates, and aquatic vegetation in the southern Everglades, with relation to environmental changes. We have studied the diets and trophic relationships of the freshwater fish community with relationship to the bioaccumulation of mercury by fishes and invertebrates. We are also documenting the use of various refuges and survival strategies of the aquatic biota during drought in the southern Florida wetland landscape. All project dates are providing empirical data and ecological rules to help build ecological simulation models used in assessing restoration alternatives.

The major clients for these projects are the NPS units of south Florida—Everglades National Park and Big Cypress National Preserve. Data will also be used by the U.S. Army Corps of Engineers in evaluating project impacts. The scope of the investigations requires the collaborations of many individuals with diverse expertise: Oron L. Bass, Walter Meshaka, and Sue Perry—Everglades National Park; Donald DeAngelis, USGS—University of Miami; Anne-Marie Eklund, NMFS—Southeast Fisheries Center; Mindy Nelson, University of Miami; Janet Reid, U.S. National Museum; and Joel C. Trexler, Florida International University.

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Mercury Transfer through an Everglades Aquatic Food

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High levels of mercury found in animals from the Florida Everglades was the impetus for this study, which began in March 1995 and has now been completed. The major funding sources for this work are the Florida Department of Environmental Protection, the South Florida Water Management District, and the National Park Service areas. We were interested in studying the processes by which mercury is made available to the biota, the extent of contamination in species at various trophic levels, and the pathways by which mercury is passed through the Everglades biota, which were poorly understood. Past studies of mercury focused on the top-level predators in the Everglades, with little analytical emphasis being placed on the smaller fishes and invertebrates upon which the predatory fishes, wading birds, and small alligators feed. Our objectives were to understand the extent of the contamination problem, and to identify the most important routes by which mercury is being passed to the top levels in the system. The project was divided into three segments: Element I described the food habits and trophic positions of Everglades freshwater fishes during high-water periods; Element II was the study of total mercury concentrations in Everglades freshwater biota, as related to trophic position, at one study location; and Element III examined the effects of time-of-year and site hydroperiod on mercury levels of wild and caged mosquitofish at three pairs of Everglades locations.

In Element I, samples from past food-habits analysis, supplemented by specimens taken during the course of this project, yielded nearly 3,000 stomachs examined for diet. The samples included 32 native and introduced species from central Shark Slough in Everglades National Park. Approximately 600 fish had empty stomachs. If sample sizes were adequate, specimens of each species were split into two or more size classes to detect changes in diet with growth. Because the mercury project coincided with a period of unusual high water levels in the Everglades, we used only the diet data for fishes collected at high-water times in our analyses of diet and trophic position (~1,500 fishes). For an independent assessment of trophic placement of animals in the aquatic food web, we collected >500 field specimens for stable-isotope analysis. Major prey types included periphyton for species like the sailfin molly and sheepshead minnow, detritus and algae for the flagfish and spotted tilapia, small invertebrates for the killifishes and livebearers, and larger aquatic insects and decapods for most sunfishes and catfish. The Florida gar, largemouth bass, pike killifish, and bowfin were at the top of the piscine food web. Based on the gut contents, the fish species were classified quantitatively into functional groups of herbivore, omnivores, and carnivores.

For Element II, 696 large-bodied and 327 small-bodied fish samples, 620 invertebrate samples, and 46 plant samples were analyzed for total mercury concentration. We also ran samples of water and soils from the study sites for total and organic mercury levels. We performed whole-body acid digestions in sealed glass ampules prior to total mercury analysis with a Merlin8 atomic fluorescence spectrometer. Total mercury levels in the whole-body digestions varied within and among taxa. Total mercury levels in microinvertebrates ranged from about 5 to 636 ng g⁻¹; macroinvertebrates, depending on the species. Typically, nonaquatic herbivores, such as marsh grasshoppers were lowest and predators, such as water bugs and spiders were highest. Most invertebrates in Shark Slough had mercury levels in the 25 to 200 ng g⁻¹ range. Small-bodied fishes also varied: the omnivorous flagfish ranged from 78 to 109 ng g⁻¹, the omnivorous mosquitofish ranged from 60 to >400 ng g⁻¹ depending on the location of the sample, and the predatory golden topminnow ranged from 101 to 886 ng g⁻¹. Some larger, longer-lived fishes had total Hg values that were lower than some of the small fishes and shrimp. For example the lake chubsucker, an invertivore, ranged from 50 to 243 ng g⁻¹. However the

larger, predatory species had the highest concentrations: largemouth bass ranged from 590 to 1150 ng g⁻¹, and the Florida gar ranged from 863 to 1515 ng g⁻¹. These data ranges closely correspond to data reported for those taxa by researchers in the northern Everglades. The large differences in total Hg concentrations apparent among groups of the 29 fish species were positively correlated with the trophic position of the fishes determined from the gut content analysis. Similarly, the concentrations of total mercury varied among the 40 invertebrate taxa, which again were positively correlated with the trophic position of those taxa as estimated from the literature. The results strongly suggest that bioaccumulation through the diet is a strong determinant of mercury concentration in fishes and invertebrates in the Everglades.

For Element III, twelve approximately monthly collections of wild mosquitofish for total mercury (2,067 specimens) from the six study marshes were analyzed. In the statistical analysis of the relationship of mercury to marsh hydroperiod, only nine of the sampling periods with full data sets were used. Hydroperiod significantly affected mercury concentrations, but there were interactions among marsh hydroperiod, fish size, site, and time-of-year. Fish from northern Shark Slough and from Taylor Slough generally had the highest mercury levels in the short hydroperiod marshes, whereas the opposite pattern held at the middle Shark Slough site. A complimentary experiment in Element III to control for movements away from study sites by the wild fish and to measure *in situ* uptake and growth, involved the captive rearing of low-mercury fish that were stocked into field cages at the same six sites. The fish produced in captivity were released when less than a week old (7.5-10 mm). Mercury level of the neonates typically ranged from 7-14 ng g⁻¹. Six trials were run. The field experiment demonstrated mercury uptake in the caged fish. There were interactions among time-of-year, site and hydroperiod. Differences between hydroperiod sites within locations at each trial existed and the same pattern as in the wild fish emerged. Fish in northern Shark Slough and Taylor Slough usually had higher mercury levels in the short-hydroperiod marshes, whereas the converse was seen in middle Shark Slough. Survival in the cages normally exceeded 80 percent. Growth varied with time of year, site and hydroperiod, but again the highest growth occurred in the short-hydroperiod marshes. This study element demonstrated the feasibility of using field cages to perform *in situ* experiments, addressing environmental contaminants and ecological interactions. The study results indicate that, although hydroperiod plays a role in mercury uptake in the Everglades, its effect varies with season and specific location.

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Methylmercury Degradation in the Florida Everglades

By Mark Marvin-DiPasquale¹ and Ronald S. Oremland¹

High levels of the monomethylmercury (CH_3Hg^+) have been reported in tissues for a number of animal species in the Florida Everglades (Ware and others, 1990; Roelke and others, 1991; Eisemann and others, 1997; and Cleckner and others, 1998). This neurotoxin is produced in anoxic sediments by sulfate reducing bacteria (Compeau and Bartha, 1985) which methylate atmospherically deposited inorganic mercury (Hg(II)). Methylmercury bioaccumulates in aquatic food chains where it may be taken up by benthic organisms, phytoplankton or periphyton. Apart from its transfer to biota, much of the CH_3Hg^+ produced may be microbially degraded within the sediment. Whether particular sediments are a net source or sink of CH_3Hg^+ depends on the relative rates of Hg-methylation and CH_3Hg^+ degradation. Although many earlier studies of environmental mercury cycling have focused on the former process, far fewer have considered CH_3Hg^+ degradation directly. Consequently, less is known about this latter process in natural systems. Defining the *in situ* rates of these competing reactions is critical for the development of accurate mercury models used by State and Federal managers for the Everglades. We explicitly investigated rates and processes influencing microbial CH_3Hg^+ degradation in sediments and by periphyton as part of the Aquatic Cycling of Mercury in the Everglades (ACME) field program conducted from 1995-98 in South Florida.

There are two known pathways for microbial CH_3Hg^+ demethylation, namely via organomercurial-lyase (OML) (Robinson and Tuovinen, 1984) and oxidative demethylation (OD) (Oremland and others, 1991). The former process represents a true detoxification response by bacteria, while the latter is thought to reflect the metabolism of a small organic molecule by heterotrophic (organic utilizing) bacteria. The *mer-B* operon encodes for the OML enzyme which forms CH_4 and Hg(II) from CH_3Hg^+ . This is typically followed by the conversion of Hg(II) to volatile gaseous Hg^0 , a reaction catalyzed by the mercuric-reductase enzyme encoded by the *mer-A* operon. Both methanogenic and sulfate-reducing bacteria have been shown to be involved in OD, the defining characteristic of which is the oxidation of the CH_3Hg^+ methyl group to CO_2 , either with or without concurrent CH_4 production (Oremland and others, 1991). The importance in distinguishing between these two modes of degradation lies in the potential fate of mercury in each case. The detoxification response of bacteria, in the case of OML and associated reductase, acts to remove mercury from the immediate environment by converting it to a final form (Hg^0) having a greater potential for transfer back to the atmosphere. In contrast, our preliminary results suggest that no such reductase activity is associated with the OD pathway. Thus, in situations where OD dominates CH_3Hg^+ breakdown, the final form of mercury is likely Hg(II) which is available for remethylation and arguably has a longer residence time in the aquatic ecosystem. By measuring the radiolabeled ^{14}C gaseous endproducts of $^{14}\text{CH}_3\text{Hg}^+$ degradation (that is, $^{14}\text{CO}_2$ and $^{14}\text{CH}_4$) we are able to get a cursory measure of the relative importance of these two distinct pathways under various environmental conditions and among different spatial regions in the Everglades.

We have recently reported that CH_3Hg^+ is degraded at *in situ* concentrations, at least in part, by the OD pathway in Everglades sediments (Marvin-DiPasquale and Oremland, 1998). This implies that much of the CH_3Hg^+ formed in anoxic sediments, not transferred to the water column, may be actively retained in the sediments due to a dynamic cycle of demethylation-remethylation. We conclude that the OD pathway should be included in the mercury model being developed for the Everglades. Rate constants for CH_3Hg^+ degradation ranged from 0.06-0.16 d^{-1} in the floc layer surface sediment, decreasing with sediment depth and increasing from nutrient enriched to more pristine areas. These within-site and among-site spatial trends were similar to those observed for Hg-methylation rates and *in situ* sediment concentrations of both total mercury and CH_3Hg^+ (Gilmour and others,

1998). We infer that there exists a tight coupling between processes of CH_3Hg^+ production and consumption in this system. In comparing gross rates of these two processes it appears that CH_3Hg^+ production exceeds degradation at all sites investigated to date. This is one factor which accounts for the accumulation of CH_3Hg^+ in Everglades biota.

Nutrient enrichment experiments (NO_3^- and PO_4^{3-}) indicated that these compounds did not directly affect rates of CH_3Hg^+ degradation, suggesting that changes in pools of porewater nutrients resulting from the ongoing construction of stormwater treatment areas will have little impact on rates of CH_3Hg^+ degradation directly. However, it is yet unclear how secondary effects due to changes in organic deposition rates, macrophyte and periphyton community structure, resident microbial populations, and the biogeochemical cycling of organic and inorganic material, resulting from the stormwater treatment areas, will impact CH_3Hg^+ degradation rates. Indeed, a general increase in degradation rate constants from 0.06 d^{-1} to 0.14 d^{-1} was observed in floc layer sediments during January 1998 along the north to south transect from Loxahatchee Wildlife Refuge to the southern reaches of Taylor Slough (unpublished data).

Since mercury input to the Everglades is primarily derived from atmospheric sources, periphyton at the water surface may intercept particle bound mercury before it can be advectively transported to the sediment. Collaborative ACME data indicates that some of these mats may be able to carry out Hg-methylation. Our unpublished results indicate that various forms of natural periphyton also have the capacity to degrade CH_3Hg^+ . The highest rates of degradation ($> 0.2 \text{ d}^{-1}$) were observed with calcareous mats that are abundant in pristine areas of the Everglades. These rates were equal to or greater than those observed in surface floc sediment samples. It is assumed that this degradation is carried out in low oxygen microzones where anaerobic bacteria are able to exit. Light/dark incubation experiments suggest an interesting diel cycle, where CH_3Hg^+ is abiotically photodegraded during the day when the photosynthetic production of oxygen inhibits anaerobic bacteria. In the evening, oxygen levels are rapidly depleted and CH_3Hg^+ is microbially degraded by the active population of anaerobes. Although these results are preliminary, they suggest a novel dual route for CH_3Hg^+ degradation associated with complex bacterial/algal mat matrices heretofore unexplored.

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Simulation Model of the Snail Kite

By Wolf M. Mooij¹ and Donald L. DeAngelis²

The snail kite (*Rostrhamus sociabilis plumbeus* Ridgway) is an endangered raptor whose North American distribution is limited to the freshwater marshes of southern and central Florida. The viability of the snail kite population is strongly linked with the hydrology of the system, due to the kite's almost total dependence on apple snails, which require a freshwater habitat. The number of habitat sites is limited and geographically separated. These sites are subject to both natural and anthropogenic drydowns, which can depress apple snail availability and affect the snail kite population.

To attempt to predict the effects of water regulation strategies across the snail kite's range on the population, an individual-based model has been developed for the population as part of the "Across Trophic Level System Simulation" (ATLSS) package of models. The model aims at predicting the viability of the snail kite population under a range of hydrologic scenarios. It is hypothesized that this viability depends critically on the frequency of droughts, but also on the spatial extent of these droughts. A systemwide drought is likely to result in increased mortality, whereas the birds can respond to a local drought by migration. The model allows one to study the effects of both drought frequency at local habitat sites and the amount of correlation of droughts among the sites.

Fourteen of the major wetlands of southern and central Florida that are inhabited by snail kites are discriminated in the model. An additional spatial unit, called peripheral habitat, is created to mimic the scattered pieces of wetlands that provide some suitable habitat for kites, though not of sufficient quality for nesting. Each kite in the population is modeled as an individual, and at a given moment in time each is located in one of these fifteen spatial units. Kites can move from wetlands to wetlands throughout their life cycles. The historical water levels in each wetlands are estimated based on water stage gauges. Possible future water levels under various water regulation scenarios are forecast using hydrologic models. The habitat quality of each wetlands is modeled on the basis of the standardized water levels. When water levels drop below a threshold, L_{low} , the state of the wetlands changes from *high* to *low*. When water levels drop below a second, lower threshold, L_{elow} , the state of a wetlands changes from *low* to *elow*. The state of a wetlands changes from *low* to *high* after a time lag, t_{low} , starting from the moment that the water levels exceed L_{low} . From *elow* the system moves to a state *lag* after a time lag t_{elow} , starting from the moment that the water levels exceed L_{elow} . From *lag* the state changes back to *high* after a time lag t_{lag} . Besides direct effects of hydrologic conditions on the kite demographics via relative habitat quality, the concept of density dependence is entered by assigning a carrying capacity to each of the 14 wetlands and the peripheral habitat. An estimate of degradation of the wetlands through prolonged continuous flooding is also included in the model.

Each snail kite in the population is simulated on a weekly basis. In a single week a kite may experience such activities as nest initiation, nest failure, successful fledging, movement to another wetland site, or mortality. Each kite goes through a fixed set of life stages. These life stages affect the probabilities with which the processes of breeding, movement, and mortality occur. The nest period is divided into three periods: the incubation stage of 4 weeks, the nestling one stage of 2 weeks, and the nestling two stage of 3 weeks, following which fledging occurs. After that there are fledgling, juvenile, subadult, adult, and senile stages. The maximum age is 20 years. Based on empirical data, parameters are assigned as probability distributions for fecundity, nest initiation, nest failure, movement to a new wetland site, and mortality.

The model shows that high drought frequencies lead to reduced numbers of kites. The effect of habitat degradation after a prolonged period of flooding, however, had no effect within the range of dry-down intervals that was studied, though it certainly would if these intervals were increased sufficiently. The most interesting aspect of the model is that it allows for the evaluation of spatial correlation between droughts. When the spatial correlation between droughts is low, the model shows narrow ranges of predicted numbers of kites. When droughts occur mostly on a systemwide level, the effect of environmental stochasticity strongly increases the unpredictability of the future numbers of kites and in the worst case the viability of the kite population is seriously threatened.

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Monitoring of Surface-Water Flows and Nutrient Loads on Tribal Lands in Southern Florida

By Mitchell H. Murray¹

The U.S. Geological Survey (USGS) established three monitoring sites south of Lake Okeechobee in an effort to accurately gage flows in canals entering and exiting tribal lands: the Big Cypress National Preserve, and Water Conservation Area 3A (WCA-3A) in southern Florida. These flows are being monitored as part of a multiagency effort to calculate nutrient loads in the canals that cross or border tribal lands. Two of the gaging sites, L-28U and L-28IN, are located on the southern border of the Seminole Indian Tribe of Florida lands along the L-28 canal and the L-28 Interceptor canal, respectively, west of WCA-3A in Hendry County. The third gaging site, L-28IS, is located along the L-28 Interceptor canal where flows enter the western lands of the Miccosukee Indian Tribe from the Big Cypress National Preserve in Collier County.

Acoustic instrumentation, in lieu of standard methods for field data collection and flow computations, is used to gage flows in the canals. With the acoustic velocity meter and the Acoustic Doppler Current Profiler, it is possible to more accurately gage flows in this type of environment because of their capability to quickly measure low or rapidly changing water velocities. Construction, instrumentation, and calibration of the flow gaging sites were completed by the USGS. The South Florida Water Management District (SFWMD) installed flow-weighted samplers at the gaging sites for nutrient analysis in conjunction with the streamflow monitoring; the flow-weighted samplers are serviced by the Seminole and Miccosukee Indian Tribes, respectively. Real-time telemetry programming assistance and phosphorus and nitrogen load calculations are provided by the SFWMD.

The L-28U site along the L-28 canal is used to monitor freshwater flows to and from the lands of the Seminole and Miccosukee Indian Tribes and to provide nutrient data as a source of information for projects by various Federal and State agencies. Total flow was recently determined by the USGS to be 89,000 acre-feet per year, representing twice the inflow amount determined by the SFWMD at their upstream USSO site located on the northwestern border of the Seminole Indian Tribal lands. From September 1997 to April 1998, the flow-weighted mean concentration of total phosphorus was 120 parts per billion at the L-28U site. The total nutrient load was 7,037 kilograms at this site compared to 1,528 kilograms at the upstream USSO site for the same 8-month period. Increases in discharge and nutrient loads at the L-28U site suggest that water, with a total phosphorus content that probably is higher than that from the USSO site, enters the L-28 canal downstream of the USSO site.

The L-28IN site along the L-28 Interceptor canal is used to monitor flows from the lands of the Seminole Indian Tribe to the Big Cypress National Preserve and to provide nutrient data for water-resources planning and management. From September 1997 to April 1998, two sampling methods (autosampler and grab samples) were used by the Seminole Indian Tribe to determine the flow-weighted mean concentration of total phosphorus. The flow-weighted mean concentration of total phosphorus determined with the autosampler was 101 parts per billion, and the mean concentration determined from the grab samples was 65 parts per billion. Theoretically, there should be no significant difference between the results as determined by the two sampling methods. Further investigation is in progress to accurately assess quality assurance procedures for weighting of flows with the autosampler.

The L-28IS site along the L-28 Interceptor canal is used to monitor flows from the lands of the Seminole Indian Tribe and the Big Cypress National Preserve to the lands of the Miccosukee Indian Tribe. This site also will be used to provide nutrient data for water managers, and has been instrumental in bracketing and quality assuring the flow calibration conditions for the upstream L-28IN site. Total flow distribution was recently determined by the USGS to be 73,000 acre-feet for the period from September 1997 to April 1998. Total phosphorus results are unavailable at the present time; however, analysis of nutrient loads and subsequent flow-weighted calculations by the SFWMD will be included in the upcoming Fourth Semiannual Progress Report submitted by the SFWMD Headquarters in West Palm Beach.

The implementation of strategically placed streamflow and water-quality gaging sites in the interior of southern Florida provides information for water managers useful to determine future surface-water flow requirements in the interior canal system. Subsequent studies based on accurate flow determinations from these sites will be used for computation of nutrient loads in the interior canal system. Providing continuous flow data at selected critical points for interior basins will compliment that from the eastern flow canal discharge network and allow for surface-water releases that are more accurately timed to deliver water when and where it is needed.

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Cape Seaside Sparrow Model, SIMSPAR

By M. Philip Nott¹ and Donald L. DeAngelis²

A spatially explicit individual-based model (SIMSPAR) was developed as a management tool for the Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*) of the Florida Everglades, as part of the “Across Trophic Level System Simulation” (ATLSS) package of models. Concern for this endangered seaside sparrow centers on reversing the declining population trend and developing appropriate management policies for hydrology and fire. A detailed approach to modeling the population viability under different water regulation scenarios is feasible because the main threat to the population is disruption of reproduction due to flooding, which can be simulated through a combination of hydrologic modeling and modeling of the reproductive phase of the sparrow life cycle. The behavior of the sparrows during reproduction and the influence of water levels on the initiation or continuation of reproductive behavior are relatively well known from field studies.

Conceptually, the model is designed as follows, based on empirical information.

(1) The landscape of the sparrow’s range is modeled explicitly as a set of spatial cells of fine enough resolution (500 x 500 meters) to represent areas of similar vegetation, topography, and hydrology. Relations were identified between habitat type within a cell and its carrying capacity in terms of the maximum density of breeding territories. Water levels in each given cell were modeled on a daily time step.

(2) Each individual sparrow in the population is modeled during the breeding period. In particular, the model tracks the sex, age, location and breeding status of each model individual from the egg stage to the end of its life. For mature males, the model tracks the establishment of breeding territories, finding a mate, the start of nesting, and the status of eggs and nestlings on a daily basis.

(3) The relation between sparrow breeding activity and water depth is modeled. A spatial cell is not available for breeding activity until the water level in that cell falls below a threshold of 5 centimeters. Any rise in the water level above 16 cm in a particular spatial cell during the nesting season is assumed to cause nest abandonment to the sparrows that have nests in that cell.

(4) The sparrows are not modeled in detail during the nonbreeding season, as that part of the annual cycle is probably not as sensitive to anthropogenic environmental conditions. Age-specific mortality rates are assigned during that period probabilistically (that is, the model is a Monte Carlo simulation), based on empirical data. The following spring, when the next breeding season begins, older males return to their previous nesting territories. If they fail to breed successfully the year before, they move to a new habitable location, if one is available, as close as possible to the site they used last year.

(5) In order to compare the model predictions with empirical data, in which only singing males are counted, the model simulated the helicopter survey, allowing a “virtual” helicopter to survey the model landscape in the same way that the observations were made in the field.

The Cape Sable sparrow model has been applied to a main subpopulation (the “western” subpopulation, or subpopulation A) of the Cape Sable seaside sparrows on the western side of Shark Slough in the Everglades National Park/Big Cypress National Preserve. Six data points for total numbers in this region were available (1981, 1992-96). Calibration and verification of the model was done using historic hydrologic data to determine water levels in the cells from 1977-96. By trial and error, an initial population size was found for 1977 such that the model produced the population number observed in 1981. Using this initial value calibration, the model predictions were validated against that data on population numbers for 1992-96. The model correctly predicts the rapid decline in population during the relatively wet years from 1992-96.

The behavior of the model was explored with respect to three measures of population viability: (1) mean time to population extinction, (2) probability of the population exceeding a specified value over time, and (3) probability of the population reaching some specified number sometime during the simulation. Sensitivity analysis was performed with the model with respect to the model's parameter values. Two parameter values in particular, female mobility and annual mortality rates, were found to be critical and to strongly influence the three measures of population viability.

The model has been used as one of the key species assessment tools in the Central and Southern Florida Comprehensive Project Review Study (Restudy). Changes to the hydrology of the southern Everglades, planned as part of a Everglades restoration project, could increase the water levels in parts of the sparrow's range and inadvertently increase the risk to the reproductive success of the sparrow in certain areas. It is critical to predict how serious these risks are. Because the model is a Monte Carlo simulation, reflecting the demographic stochasticity that occurs in real populations, numerous replicate simulations can be performed over a given time period, so that the means and variances of the three measures of population viability can be computed.

The model also allows the computation of a spatially explicit "breeding potential index" that estimates the potential number of successful broods that can be achieved during a given year, under given hydrologic conditions, in each spatial cell of appropriate vegetation type. This index is based on continuous days in which the cell is dry during the breeding period.

The Cape Sable sparrow model output was used in evaluating alternative water regulation scenarios as part of the Restudy. At this time, however, the model does not take into account possible changes in habitat through time, due to fire or prolonged changes in hydrologic conditions. We are currently working to achieve this.

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Sulfur Contamination in the Everglades and Its Relation to Mercury Methylation

By William H. Orem¹, Anne L. Bates¹, Harry E. Lerch¹, Margo Corum¹, and Ann Boylan¹

High levels of toxic methylmercury in fish and other biota in the Everglades is a serious threat to the vitality of this ecosystem, and poses a potential human health concern. The biogeochemistry of sulfur in the freshwater Everglades is important, because the reduction of sulfate to sulfide in anoxic marsh sediments is linked to methylmercury production through processes mediated by sulfate-reducing bacteria. The objectives of this project, in collaboration with the Aquatic Cycling of Mercury in the Everglades group were to: (1) examine the distribution of sulfur species in the Everglades spatially and temporally, (2) determine the relation, if any, in the observed distribution of sulfur to mercury methylation, and (3) examine the source(s) of sulfur to the Everglades using sulfur isotope geochemistry as a tracer tool. Our results to date indicate that excess sulfate enters the northern Water Conservation Areas (WCA) in water discharged from canals draining the Everglades Agricultural Area (EAA). This excess sulfate probably originates from agricultural sulfur used in the EAA. Studies of dated cores from WCA-2A show that the influx of excess sulfur began in the early part of this century, concomitant with an influx of excess phosphorus (Craft and Richardson, 1993). The excess sulfate stimulates bacterial sulfate reduction over large areas, and has a significant but complex relation to the extent and distribution of methylmercury in the ecosystem (Gilmour and others, 1998).

Studies of sediment cores collected in WCA-2A indicate trends of increasing concentrations of total sulfur (TS) in sediments during the last century (Bates and others, 1998). At a site near the discharge of water from the Hillsboro Canal, TS concentrations in sediments below 25-30 cm depth held fairly steady at about 0.7 percent (dry wt.). Above this depth, corresponding to the early part of this century, TS concentrations in the core increase sharply to concentrations of about 1.5 percent. This increase in TS correlates closely with increases in total phosphorus observed at this site, and suggests that the load of sulfur and phosphorus to the sediments at this location have increased during the last century. A similar increase in TS near the surface is also observed at a site in the center of WCA-2A, although no concomitant increase in total phosphorus was observed. This suggests that phosphorus entering the ecosystem is quickly sequestered by aquatic macrophytes near canal discharge sites; in contrast, sulfur is an element having greater mobility in this wetland environment. Accumulation rates of TS in surface sediments are about 5 times higher at the Hillsboro Canal site compared to the site in the center of WCA-2A. The principal form of TS in sediments at all marsh sites is organic sulfur, reflecting the reaction of bacterially produced sulfide with organic matter in the sediments. Relatively low levels of iron in the ecosystem is apparently limiting the formation of disulfide minerals in the sediments.

Sulfate concentrations in surface water from WCA-2A are typically 20 to 60 mg/L, with values up to 120 mg/L, near points of water discharge from the Hillsboro Canal. In contrast, surface-water sulfate concentrations from the center of pristine WCA-1A are typically < 1 mg/L. Porewater sulfide concentrations are also elevated in WCA-2A (concentrations often > 2,500 µg/L) compared to concentrations of < 0.1 µg/L in the center of WCA-1A. The high levels of sulfide in porewaters from WCA-2A reflect high rates of sulfate reduction in the anoxic sediments (porewater Eh values typically in the range of -200 mv), stimulated by the high levels of sulfate in the wetland. High levels of surface-water sulfate and porewater sulfide are prevalent throughout WCA-2A, attesting to the general mobility of sulfur within the wetland ecosystem. In contrast to phosphorus contamination, which is confined at present to a broad swath of WCA-2A bordering the Hillsboro Canal, sulfur contamination extends to the center of WCA-2A. Sulfate concentrations in surface water and sulfide concentrations in porewater in the center of WCA-2A are nearly as high as those observed at sites located near points of water discharge from the Hillsboro Canal. Sulfur contamination has also been observed in WCA-3A, but to a lesser degree than in WCA-2A. At a

site adjacent to the Miami Canal in WCA-3A, surface-water sulfate concentrations of 30 mg/L, and porewater sulfide concentrations of about 500 ($\mu\text{g/L}$) were observed. At a site farther south near the center of WCA-3A (site 3A-15), surface-water sulfate concentrations ranged from 2 to 12 mg/L, and porewater sulfide concentrations varied between 1 and 100 $\mu\text{g/L}$. Still farther south at several sites in WCA-3A and 3B near Tamiami Trail, surface-water sulfate concentrations were typically < 1 mg/L and porewater sulfide concentrations were < 0.1 ppb. The following pattern emerges from these results: (1) heavy sulfur contamination in all of WCA-2A, but with the highest levels near sites of water discharge from the Hillsboro Canal; (2) generally lower levels of sulfur contamination in WCA-3A compared to WCA-2A, and with the levels of sulfur contamination decreasing toward the south, away from the Miami Canal; and (3) background levels of sulfur for the Everglades at sites in the center of WCA-1A and in the far southern reaches of WCA-3A and B.

An extensive survey of sulfate concentrations and isotopic composition ($\delta^{34}\text{S}$) in: (1) surface-water samples from Lake Okeechobee, canals draining the EAA, and marshes of the WCA, (2) ground-water samples from the WCA and the EAA, and (3) rainfall. The survey was to determine the major source(s) of sulfur contamination to the northern Everglades (Bates and others, 1999). Rainwater has far too low a concentration (< 1 mg/L) and isotopic composition ($\delta^{34}\text{S} = +2$ to $+11$) to account for the sulfur contamination in the marshes (sulfate concentrations of 20-60 mg/L and typical $\delta^{34}\text{S}$ values of $+20$ to $+25$). Similarly, ground-water samples from sites in WCA-2A and the EAA (except for ground water deeper than 8 m) have been eliminated as sources of sulfur contamination, either because of very low sulfate concentrations, and/or sulfur isotope compositions incompatible with those observed in the marshes. In contrast, canal water draining the EAA has variable, but usually high sulfate concentrations (35-180 mg/L), and an isotopic composition compatible with sulfate present in the marshes. Although these canals originate at Lake Okeechobee, the lake water has sulfate concentrations too low (< 10 mg/L) to account for most of the sulfate in the canals. Furthermore, the sulfate in the canals of the EAA has an isotopic composition similar to that of agricultural sulfur used on fields in the EAA ($\delta^{34}\text{S} \approx +16$). Deep groundwater (> 8 m) below the EAA also has sulfate concentrations and a sulfur isotopic composition consistent with the sulfur contamination in the WCA. It may be that both agricultural sulfur and deep ground-water contribute to the very high sulfur concentrations observed in the EAA canals and the northern WCA.

In conclusion, high concentrations of sulfate originating from canals draining the EAA are resulting in extensive sulfur contamination of the WCA. Sulfur contamination in WCA-2A appears to have started during the early part of this century, concomitant with phosphorus contamination here. High concentrations of sulfate in WCA-2A are stimulating bacterial sulfate reduction, but the high levels of sulfide in porewaters here apparently inhibit mercury methylation (Hayes and others, 1998). Lower levels of sulfate contamination in the center of WCA-3A apparently increase sulfate reduction and mercury methylation without the inhibitory effects of excess sulfide on mercury methylation.

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Nutrient Geochemistry of the South Florida Wetlands Ecosystem: Sources, Accumulation and Biogeochemical Cycling

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The south Florida wetlands ecosystem (the Everglades and Florida Bay) has historically been an oligotrophic environment. Anthropogenic activities (especially agriculture) during the past century, however, have delivered excess phosphorus (P) to some areas of the northern Everglades, contributing to changes in water quality and ecology. The fate of this excess P and its long-term effects on biological resources are unclear. South of the Everglades, changes in nutrient loads to Florida Bay are hypothesized to be linked to recent events of seagrass die-off and microalgal blooms. Restoration of the Everglades and Florida Bay to a more natural nutrient balance will require crucial baseline information on the ecosystem's recent nutrient history, the sources of nutrients to the ecosystem, and the biogeochemical cycling of nutrients within the ecosystem. This project³ has focused on establishing: (1) the source(s) of nutrients to contaminated areas of the northern Everglades and to Florida Bay, (2) the spatial and temporal variation of nutrients within the ecosystem, and (3) the rates of accumulation and recycling of nutrients in sediments (including the flux of nutrients from sediment porewater to surface water).

Our results show that concentrations of P at pristine sites in the freshwater Everglades range from 1-20 µg/L in surface water, 10-100 µg/L in sediment porewater, and 300-500 µg/g (dry wt) in sediments. At contaminated marsh sites, however, P concentrations often exceed 100 µg/L in surface water, 3,000 µg/L in porewater, and 2,000 µg/g in surface sediment. Profiles of total P in dated (²¹⁰Pb and ¹³⁷Cs) sediment cores from Water Conservation Area (WCA) 2A show that greatly increased loads of P were delivered to sediments near the Hillsboro Canal from the 1920's to the present. The area of P contamination is currently confined to a band in WCA-2A adjacent to the Hillsboro Canal and other marsh sites adjacent to canals in the WCA. Cattails (eutrophic macrophytes) have colonized the P-contaminated areas, displacing the oligotrophic sawgrass. Accumulation rates of P in sediment at contaminated sites are typically 100 times higher compared to pristine areas. Porewater at contaminated sites, however, also has 30-300 times higher concentrations of P than pristine sites. This suggests that the rate of microbial recycling of P and the flux of P from porewater to surface water is also much higher at contaminated sites. This may reflect both nutrient stimulation of microbial activity and the chemical lability of organic matter in the eutrophic cattails present in P-contaminated areas. Hence P, while rapidly accumulated in contaminated areas, is also rapidly recycled. The balance between P accumulation and recycling in marsh areas dominated by eutrophic macrophytes is critical for estimating the long-term effectiveness of constructed wetlands (which will likely contain mostly eutrophic macrophytes) designed as nutrient buffer areas to protect the Everglades.

We have used the concentration and alpha activity ratio (²³⁴U/²³⁸U) of readily exchangeable uranium (U) as a geochemical tracer to examine the source(s) of P to the northern Everglades. This approach is predicated on the high concentration of U in phosphate rock used to make phosphate fertilizer (correlated with P concentration), and its distinctive activity ratio (AR) of 1.00 ± 0.05 . The concentration and activity ratio of U was determined in fertilizer used in the Everglades Agricultural Area (EAA), in sediment cores, and in surface water from: the Kissimmee River and creeks entering Lake Okeechobee, Lake Okeechobee, canals and fields in the EAA, and marsh sites in the WCA. Sediments from P-contaminated sites in WCA-2A near the Hillsboro Canal had U concentrations in

excess of 1 $\mu\text{g/g}$, and uranium AR ranging from 0.97-1.03, values permissive of a fertilizer source. In contrast, a pristine site in the center of WCA-1A had U concentrations of $< 0.2 \mu\text{g/g}$ and AR values of 1.10-1.22, inconsistent with a fertilizer source. Concentrations of U in canal water from the EAA average about 0.3 $\mu\text{g/L}$ and have AR values of around 1.00, permissive of a fertilizer source. These results suggest that the source of U (and by analogy P) in contaminated areas of WCA-2A is P fertilizer used in the EAA, and affirm previous assumptions about P contamination in the Everglades.

In preliminary work, we have determined that tree islands represent another zone of P enrichment in the Everglades. Studies of sediments from the heads of two tree islands in WCA-3B showed concentrations of up to 3,000 $\mu\text{g/g}$ on one island and up to 1,500 $\mu\text{g/g}$ on the second. These concentrations are far in excess of those observed in the surrounding pristine marsh (values of around 200-300 $\mu\text{g/g}$), and approach or exceed P concentrations in contaminated areas of WCA-2A. The source of the high levels of P on tree islands is uncertain, but we hypothesize that it originates from the guano of nesting birds. The P concentrations of sediments in the tail and edge of the tree island are also in excess of concentrations in the surrounding marsh, but less than values found on the head. Runoff of P from the head may explain the distribution of P in the tail, and P-enrichment may play a role in the development of tree island tails.

In the southern Everglades, we have conducted extensive sediment and water sampling in Taylor Slough and the C-111 basin. In addition, water sampling and sediment coring have been undertaken at sites in Florida Bay and the mangrove fringe zone surrounding Florida Bay. The objective of this work was to examine source(s) of nutrients and nutrient cycling in the southeastern Everglades and northeastern Florida Bay. Analysis of samples and data from this study is still underway; some preliminary conclusions, however, have been developed. Concentrations of total P in sediments at the head of Taylor Slough approach values of 1,000 $\mu\text{g/g}$, in excess of concentrations for pristine areas of the Everglades. This suggests P contamination at the head of Taylor Slough from canals discharging at the head of the Slough. Total P concentrations in sediments diminish to the south to nearly background levels ($< 500 \mu\text{g/g}$) by the center of the Slough. Accumulation rates for P range from 1.4 $\text{gP/m}^2\text{-yr}$ at the head of the slough to only 0.04 $\text{gP/m}^2\text{-yr}$ at midslough. Although concentrations of total P in Florida Bay sediments range from only 100-300 $\mu\text{g/g}$, P accumulation rates in Florida Bay (0.2-1.4 $\text{gP/m}^2\text{-yr}$) are higher than those in pristine areas of Taylor Slough. Surface water and sediment data show that Taylor Slough is not a major source of P to northeastern Florida Bay under current hydrologic flow conditions. Preliminary results suggest that Florida Bay may actually serve as a source of nutrients to the mangrove fringe zone between Taylor Slough and Florida Bay. Downcore profiles at several sites in eastern and central Florida Bay show surficial anomalies of P and N concentrations that suggest recent increases in nutrient load to the sediments, beginning in the early 1980's. It is unclear if these anomalies represent anthropogenic inputs of nutrients to Florida Bay. It is noteworthy, however, that downcore profiles at sites of relatively slow sedimentation in central Florida Bay show significant anomalies in total nitrogen and organic carbon on a decadal timescale, with extrapolated dates (^{210}Pb) in the mid-1700's. This may have been a period of increased rainfall in south Florida and concomitant increased hydrologic flow to Florida Bay, with the effect of increasing nitrogen input to the bay, and triggering an increase in productivity. Thus, periods of increased nutrient input to the bay can follow natural, climate-driven cycles, as well as being influenced by anthropogenic input.

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Estimating Freshwater Flows into Northeastern Florida Bay

By Eduardo Patino¹

Historical changes in water-management practices to accommodate a large and rapidly growing urban population along the Atlantic coast as well as intensive agricultural activities, have resulted in a highly managed hydrologic system with canals, levees, gated control structures, and pumping stations. These structures have altered the hydrology of the Everglades ecosystem, including Florida Bay. The bay, home to several endangered species, is a valuable breeding ground for marine life and an important recreational and sport fishing area. The bay encompasses an area of about 850 square miles with an average depth of less than 4 feet. It is bordered by the mainland portion of Everglades National Park to the north, the Florida Keys to the east and south, and the Gulf of Mexico to the west.

Planning for restoration of the south Florida ecosystem includes the use of hydrologic and hydraulic models that simulate the flow of water through the region based on various water-management practices. The measurement and determination of flow along model boundaries is of great importance for the development and verification of these models. In October 1994, the U.S. Geological Survey, as part of its South Florida Ecosystem Program, began a study to measure flows into Florida Bay from the mainland through the streams along the northeastern coast. This study is providing modelers with essential data along the mangrove zone where data have not been previously available. Flow through the mangrove zone in northeastern Florida Bay is naturally controlled by the wet or dry conditions of the Everglades wetlands, regional wind patterns, and, to some extent, by tidal action on the western part of the bay from the Gulf of Mexico. This flow of freshwater from the mainland into northeastern Florida Bay is mostly confined to several streams or creeks, except during extreme high-water conditions when significant sheetflow can be observed through low-lying mangrove areas between the streams.

Ten stream sites along the southern Florida coastline were selected for the study to determine the magnitude of freshwater flows into northeastern Florida Bay and to describe the general flow characteristics of these streams. Several agencies, including the U.S. Geological Survey, U.S. Army Corps of Engineers, and the South Florida Water Management District, are developing hydrodynamic models to simulate and predict the movement of water in the mainland, flows into Florida Bay, and circulation patterns within coastal waters (Florida Bay). This study provides necessary flow and salinity information for these models along the coastal boundary of northeastern Florida Bay. The data collected for the study include: (1) water level as a variable for the calculation of cross-sectional area and mean channel velocity, (2) acoustic velocity for the calculation of mean channel velocity and discharge, (3) measured discharge and velocity to develop acoustic to mean measured velocity relations, (4) salinity to help qualify the presence of saltwater and to monitor its possible detrimental effects on the acoustic signals, and (5) temperature to monitor its possible detrimental effects on acoustic signals.

In order to estimate total freshwater flows into northeastern Florida Bay, discharge at noninstrumented sites needed to be determined. To estimate mean monthly values of discharge, correlation techniques were used to establish relations between discharge at the noninstrumented sites and discharge at a nearby monitoring station. Flows in the streams along the northeastern coastline of Florida Bay do not present the typical ebb and flood tidal signatures of most estuarine streams. These tidal signatures are either nonexistent or significantly dampened as a result of three factors: (1) the numerous mudbanks that divide Florida Bay into a large number of subbasins, (2) the presence

of U.S. Highway 1 along the Florida Keys, and (3) the effects of regional wind forces. Analysis of seasonal flows indicate that about 80 percent of the total freshwater enters northeastern Florida Bay during the wet season (May through October), with a very sharp and distinct transition from brackish to freshwater occurring in the bay at the start of the wet season. Significant effects from the El Niño event on normally dry-season flows were evident based on the data, with flows increasing to a mean dry-season discharge of 273 cubic feet per second, from 41 cubic feet per second during the previous year. El Niño is also the probable cause for flows at McCormick Creek (the westernmost monitoring station) to show negative net discharges for a period starting in August 1998, unlike flow patterns shown by the rest of the monitoring stations in the area during the same time period.

Three main flow signatures also were identified when comparing flows at all monitoring stations, with the most significant one being the magnitude of discharges at Trout Creek, which carries almost 60 percent of the total freshwater entering northeastern Florida Bay. The other two significant flow signatures identified were the shifting of flow patterns at McCormick Creek during the El Niño event and the absence of “net” negative flows at the West Highway Creek site (just west of U.S. Highway 1). The observed flow distribution and especially the magnitude of flows through Trout Creek in comparison with those to the west of the creek suggest that the flow of freshwater in the Everglades wetlands along Taylor Slough may have more of an easterly movement than previously thought.

Trout Creek was selected as the base-gage for correlation analyses and used to determine if one station could be used as the indicator of effects on freshwater flows into northeastern Florida Bay caused by changes in water-management practices in the mainland. As a result of these analyses, it was determined that Trout Creek could be used as the long-term monitoring station provided that remaining questions regarding the flow patterns at McCormick Creek and Long Sound streams were answered. Data from this study will provide water managers with information regarding the distribution of discharges along the coastline of northeastern Florida Bay, which in turn, can be used to determine the magnitude and timing of water releases from the L-31W and C-111 Canal systems.

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American Alligator Distribution, Thermoregulation, and Biotic Potential Relative to Hydroperiod in the Everglades

By H. Franklin Percival¹ and Kenneth G. Rice²

This work is associated with the U.S. Geological Survey, Biological Resources Division “Across Trophic Level System Simulation” (ATLSS) program and has the objective of supplying empirical information needed to develop a population model for the American alligator (*Alligator mississippiensis*). The American alligator is not only a top consumer and a keystone species in the Everglades, but also physically influences the system through construction and maintenance of alligator holes and trails. It is presumed that the existence of this species is important to the faunal and floral character of the Everglades as it has evolved. Despite its prominence biologically and publicly in the system, many important questions about basic behavioral and population parameters of alligators remain unanswered. Although many assumptions can be made, we are not certain of movements or survival of varying size classes of alligators under either stable or fluctuating water levels. The reproductive contribution of an individual animal or of different size/age classes in any given year has been a principal stumbling block for attempts at modeling any crocodilian population. For effective modeling of alligators, more definitive answers to those latter two questions are essential.

The main objectives of this study are the following:

1. To determine daily and seasonal movements and survival of varying age/size and habitat (canal, interior marsh) classes of Everglades alligators;
2. To determine the proportion of female alligators in the population that might be expected to nest in a given year;
3. To elaborate on existing hypotheses of thermoregulation in Everglades alligators; and
4. To relate the above objectives to the dynamic hydroperiod of the Everglades and to two geographic compartments of the Everglades (Water Conservation Area-3A (WCA-3A) North and Everglades National Park).

To achieve these objectives, 29 alligators are currently being tracked in WCA-3A North and 25 alligators in Everglades National Park. Of these, 29 have been implanted with temperature data loggers. Weekly fixes have been made since the project was initiated in November 1996. Therefore, 2 years of data on home range size, movement patterns, habitat preference, and thermoregulation have been collected. Intensive week-long samples to further investigate habitat preference and daily movement patterns have been conducted as well, once in each season of the year, and the data are currently being analyzed.

Several patterns have become clear through the preliminary analysis of the data. First, in the summer, Everglades’ alligators maintain very high body temperatures due to the constant, high ambient temperature of their environment. In conditions where food is plentiful and temperatures are consistently high, such as in an alligator farm, growth is extremely rapid. However, the Everglades is currently thought to be a food limited environment for alligators. High body temperature results in high rates of metabolism, which leads to increased food demands to fuel increased maintenance cost. The poor body condition of Everglades’ alligators will likely be better understood in light of their thermal regime.

In winter, Everglades' alligator body temperatures follow the declines of ambient temperatures. This is to be expected from the habits of northern alligators that over-winter in dens. When body temperatures remain below 22 °C, alligators stop eating. By greatly reducing body temperature during over-wintering, alligators reduce metabolic cost. Preliminary analysis of body temperature during winter suggests that alligators seek the colder regions available to them. However, body temperatures rarely drop below 15 °C. During winter, Everglades' alligators frequently warm up for short periods of time. This suggests that winters in the Everglades may represent a limbo period where temperatures are not cold enough to force over-wintering in dens, but not warm enough to allow optimality in such functions as feeding. A thorough examination of winter data will likely reveal unique habits of Everglades' alligators and lead to a better understanding of alligator biology in general.

Data from early spring reveals an interesting pattern as well. While temperatures are often as low as in winter, high body temperatures are attained much more frequently. There are two factors that are likely to be responsible for this trend. First, animals are preparing to breed. Higher temperatures are likely to aid in development of reproductive hormones and tissues. The second factor is that this is the height of the dry season, when food is concentrated in holes. In order for alligators to take advantage of this resource, they must maintain high body temperature in order to digest prey items and assimilate them into body tissues.

Once the data set has been decomposed and trends analyzed, more sophisticated data analysis techniques will be employed in order to thoroughly investigate the data. Water levels and environmental temperatures will be analyzed to determine their effect on the thermal regime of the alligator. Never before has such a complete picture of a free ranging animal's thermal biology been quantified.

A significant part of the funding for this research was provided from the U.S. Department of the Interior, South Florida Ecosystem Restoration Program "Critical Ecosystems Studies Initiative" (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the "Across Trophic Level System Simulation" was provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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Mercury-Dissolved Organic Carbon Interactions in the Florida Everglades: A Field and Laboratory Investigation

By M.M. Reddy¹, G.R. Aiken¹, and P.F. Schuster¹

There is increased awareness of mercury (Hg) contamination of game fish in South Florida. Effective management strategies for dealing with this problem require understanding of processes resulting in occurrence and transport of Hg, and control of its reactivity in the Everglades. Interaction of Hg with dissolved organic carbon (DOC) has been proposed as a mechanism for Hg transport in aquatic systems because of a correlation between dissolved Hg and DOC concentrations in natural waters. Mercury DOC interactions play an important role in controlling the availability of Hg for uptake by living organisms. DOC reactivity is important in South Florida because of its high production in the peat soils, wetlands, and shallow ground-water systems in the region.

The South Florida Water Management District, the U.S. Environmental Protection Agency, and the U.S. Geological Survey South Florida Ecosystems Initiative have organized a collaborative intensive study of surface-water chemistry in southern Florida. In 1994, several onsite research locations were selected in the Water Conservation Areas of the Everglades in conjunction with this multidisciplinary, multiagency research project. Our project goal is to understand the interactions of Hg and DOC to better define this important, albeit, poorly understood process. The hypothesis is that the chemistry and structural characteristics of DOC in the Everglades have a strong influence on the processes that control Hg cycling and bioavailability in the environment.

Research accomplishments summarized here are described in detail on the WEB at http://wwwbrr.cr.usgs.gov/projects/SW_corrosion. Three areas of progress will be summarized here:

1. Field and laboratory analysis of water samples collected in the Everglades: We have completed chemical analysis for samples collected in canals and marsh sites from March 1995 to January 1998 as part of a study to quantify the interaction of DOC with Hg. Results from 11 field trips are based on onsite and laboratory measurements for 758 samples collected at 34 locations. A representative sample data set is available at our project WEB site, http://wwwbrr.cr.usgs.gov/projects/SW_corrosion. The complete data set is available at the South Florida Ecosystem WEB site (<http://fl-water.usgs.gov/exchange/exchange.html>).

Speciation of Hg in aquatic systems depends, in large part, on the pH and concentrations of DOC, sulfide, and dissolved oxygen (DO) in surface water and porewater. Spatial and temporal monitoring of these constituents, which are critical to the understanding of processes controlling Hg bioavailability, were conducted at oligotrophic (nutrient poor) and eutrophic (nutrient rich) sites in the south Florida Everglades. Close-interval vertical measurements of sulfide and DO concentrations were made both on a seasonal and diel timescale using water-quality multiprobes, a DO microprobe, and a portable spectrophotometer. Water samples were also collected for Hg, DOC, sulfate, and chloride determinations.

Oligotrophic and eutrophic sites differ with respect to production and exchange of sulfide and oxygen between the sediments and water column. The diel fluctuations of sulfide appear to be influenced by photosynthesis and availability of sulfate. The oligotrophic site exhibits a positive correlation between methylmercury and sulfide with coincident maximum concentrations near

midnight, indicating a diel response. Although the eutrophic site showed large concentration gradients and diel changes between surface water and porewater for DOC, sulfide, and DO, Hg showed no diel change.

2. Laboratory studies of DOC isolated from the Everglades: Organic matter isolated from the Florida Everglades caused a dramatic increase in Hg release from cinnabar (HgS) under most environmental conditions. Hydrophobic (humic and fulvic) acids dissolved more Hg than hydrophilic acids and other nonacid fractions of DOC. HgS dissolution was inhibited by divalent cations such as calcium ion, but was independent of oxygen content in experimental solutions. The presence of various inorganic (chloride, sulfate, or sulfide) and organic ligands (salicylic acid, acetic acid, EDTA, or cysteine) did not enhance the dissolution of Hg from HgS.

Precipitation and aggregation of metacinnabar (black HgS) was inhibited in the presence of low concentrations of DOC isolated from the Florida Everglades. At low Hg concentrations ($\leq 5 \times 10^{-8}$ M), DOC prevented the formation of metacinnabar. At moderate Hg concentrations (5×10^{-5} M), DOC inhibited the aggregation of colloidal metacinnabar. At Hg concentrations $> 5 \times 10^{-4}$ M, metacinnabar precipitated in the presence of organic matter and was removed from solution by filtration with a 0.1 μ m filter. In this precipitation reaction, organic matter rich in aromatic moieties was preferentially removed with the solid. Hydrophobic acids inhibited precipitation better than hydrophilic acids. Calcium favored metacinnabar formation even in the presence of DOC, but the magnitude of the effect was dependent on the concentrations of DOC, Hg, and calcium ion. Inhibition of precipitation appears to be a result of strong DOC-Hg binding and prevention of aggregation of colloidal particles through surface interactions.

An ion-exchange distribution method was used to determine the stability constants of Hg complexed by DOC isolated from the Everglades. For comparison, the stability constants of several inorganic (chloride, bromide) and organic ligands (citric acid, thioglycolic acid) were also determined by this method. At fixed pH (6.0) and equal ligand concentrations (2×10^{-4} M), the distribution ratio ($[\text{Hg}_{\text{resin}}]/[\text{Hg}_{\text{solution}}]$) in the presence of DOC was comparable to the values for strongly binding ligands such as thioglycolic acid ($\beta_{\text{HgL}} = 10^{30}$). Experimental constants for Hg-DOC interaction were $10^{10.3}$ to $10^{11.2}$. Differences between the expected and experimental values for model ligands (and by analogy for DOC) were attributed to the limitations of the ionexchange method.

3. Hg-DOC speciation and modeling studies: The computer ionic speciation model “WHAM” (Windermere Humic Aqueous Model) was used to characterize the Hg-organic species present in Everglades surface water. WHAM focuses on hydrophobic acid-metal interactions. These calculations indicate that the major Hg species in solution change from uncharged chloro- and hydroxycomplexes to charged DOC-bound complexes in the presence of high DOC concentrations (< 10 mg/L C). Inorganic speciation calculated using WHAM has been compared to speciation determined with PHREEQC (pH-redox-equilibrium-equations) with good agreement. WHAM has also been satisfactorily tested using laboratory measurements of calcium ion binding to a soil fulvic acid. Sulfide and sulfur containing ligands shift Hg speciation to Hg-sulfur and Hg-organosulfur complexes. Examination of Hg sulfide and Hg thiol binding constants suggests that sulfhydryl groups may preferentially bind Hg in competition with sulfide ion.

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Hydrogeology of a Dynamic Marine System in a Carbonate Environment, Key Largo Limestone Formation, Florida Keys

Christopher D. Reich¹, Eugene A. Shinn¹, Todd D. Hickey¹, and Ann B. Tihansky²

Tidal signal, wave amplitude, and wind pattern all combine to set up a unique and dynamic system that drives ground-water flow in the highly porous and permeable Key Largo Limestone. Pressure-head measurements and dye tracer experiments in underwater piezometer clusters in Florida Bay and the Atlantic Ocean have demonstrated that a net ground-water flow occurs from the bay to the ocean.

Injection of two dye tracers, fluorescein and rhodamine, as well as an inert gas solution, sulfur hexafluoride (SF_6), and subsequent monitoring in surrounding piezometers, exhibits a net submarine ground-water flow from Florida Bay to the Atlantic Ocean with velocities up to 2 meters per day. In addition, direction of flow based on tracer experiments is congruent with sea level information which indicates that Florida Bay is higher, 10 to 20 centimeters on average, than mean Atlantic Ocean sea level. The difference between bay and ocean sea level is the main driving force for ground-water flow beneath the upper Keys. However, sustained high easterly winds periodically depress the bay level, raise water level on the Atlantic side of the upper Keys, and drive marine ground water at similar velocities beneath Key Largo toward Florida Bay.

In addition, tidal pumping, a phenomenon observed in our piezometers, is the result of a difference in tides between the Atlantic Ocean and Florida Bay. Tracer studies indicate that dye injected in deep (13.6 meters) wells appear first in shallow (6.1 meters) wells 30 meters away. The vertical tracer movement may be attributed to tidal pumping. Vertical ground-water flow and, ultimately, seepage of nutrient-rich ground water into the surface water may have an impact on the diversity and health of the nearshore marine environment.

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American Alligator Ecology

Kenneth G. Rice¹ and H. Franklin Percival²

The greater Everglades of south Florida are characterized by complex patterns of spatial heterogeneity and temporal variability. Spatial and temporal hydrologic patterns (hydropattern), which result from the distribution, volume, and timing of water flow, are a major driving force controlling the trophic dynamics of these systems. After many decades of intense adverse water-management impacts, hydrologic restoration alternatives are now being developed and proposed. Thus, there is a need to predict and to compare the future effects of alternative hydrologic restoration scenarios on the biotic components of these systems. The American alligator is not only a top consumer and a keystone species in the Everglades, but also physically influences the system through construction and maintenance of alligator holes and trails. The existence of this species is important to the faunal and floral character of the Everglades as it has evolved. Despite its prominence biologically and publicly in the system, many important questions about basic behavioral and population parameters of alligators remain unanswered.

Although many assumptions can be made, there is no reasonable certainty in estimates of movements or survival of varying size classes of alligators under either stable or fluctuating water levels. The reproductive contribution of an individual animal or of different size/age classes in a given year has been a principal stumbling block for attempts at modeling any crocodilian population. This study is focused on both field experiments and statistical models to obtain estimates of the aforementioned parameters. Further, the broad project goals include end products of ecologically based ecosystem models (under the model integration framework, "Across Trophic Level System Simulation" (ATLSS) program), including predictive population model(s) for alligators to be used in evaluating restoration scenarios for the Everglades/Big Cypress ecosystems. The project incorporates the expertise of many collaborators, including Clarence L. Abercrombie of Wofford College; Timothy S. Gross of the U.S. Geological Survey; Frank Mazzotti of the University of Florida; and several biologists from the Florida Game and Fresh Water Fish Commission and the Everglades National Park.

The project includes several interrelated component studies designed to address the questions outlined above:

1. Alligator movement, habitat use and preference, survival, and breeding potential: This study uses radiotelemetry technology to monitor the movement patterns of alligators in Everglades National Park (Shark River Slough) and Water Conservation Area 3A. Over the course of the study, approximately 80 animals (partitioned into area, habitat, sex, and size classes) have been implanted with transmitters and monitored for 1-3 years. Preliminary analyses are available including estimates of home-range size, habitat preferences, nesting parameters, and movement patterns. This study is scheduled to terminate in Summer 1999.

2. Alligator Thermoregulation: Of the 80 telemetered animals discussed above, approximately 30 additionally were implanted with temperature data recorders. The recorders logged internal body temperatures every hour for 1 year. After recapture, the loggers were removed and coupled with corresponding environmental temperatures, we now have an excellent data base to address questions concerning metabolic costs of surviving in various thermal environments. This data, in conjunction with the telemetry results outlined above and further measurements of alligator holes and canals discussed below, will allow us to explore the relative role of canals and other landscape features and hydrological impacts on alligator populations. This study is scheduled for completion in Fall 1999.

3. Alligator Holes: During the course of the telemetry study, it became apparent that animals existing in natural slough habitats used the landscape in very different ways from animals living in canal systems. Marsh animals use 1 to 5 alligator holes for thermoregulation, cover, and, presumably, feeding. To better understand the role of alligator holes and canals in the life history of the alligator, we have undertaken to catalog the physical attributes of the holes or canals used by each telemetered alligator. This information will be important for the simulation models discussed below, as well as, determining the relative importance of these landscape features. This study will conclude in 2000.

4. Breeding Potential Index: As a component of ATLSS, the alligator breeding potential index provides an estimate of the relative rate of successful offspring production under varying hydrological conditions in south Florida. The model uses index estimates for nesting potential, habitat conditions, and nest-flooding potential to construct an index value for each 500-meter cell in the greater Everglades ecosystem. When fully functional, the index will provide comparisons of each alternative and base condition under the Central and Southern Florida Comprehensive Project Review Study (RESTUDY). We hope to have a verified index in place on the ATLSS website by Spring 1999.

5. Population Model: A matrix-based population simulation model for the alligator in south Florida will be constructed during 1999-2000. This model, although having the same underlying goals of the above index (to explore the effects of varying hydrological alternatives on alligator populations), will investigate other life-history parameters. In concert with this model, historical data sets will be located, and a data base of alligator ecology studies will be produced. When coupled with the outputs from other existing models, the alligator population model will provide estimates of survival, fecundity, and growth (both individual and population) under each Restudy alternative and will be incorporated into the ATLSS program.

A significant part of the funding for this research was provided from the U.S. Department of the Interior, South Florida Ecosystem Restoration Program "Critical Ecosystems Studies Initiative" (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center.

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Temporal and Spatial Variation in Seagrass Associated Fish and Invertebrates in Johnson Key Basin, Western Florida Bay

By Michael B. Robblee¹ and Andre Daniels¹

Everglades National Park is known for the numerous water resource problems assailing the integrity of its marine and freshwater ecosystems. Maintenance of the health and function of these systems is a central focus of the South Florida Restoration Program. This project documents fish and invertebrate community composition in western Florida Bay in order to assess the bay's response to seagrass and environmental changes over time. Florida Bay is a subtropical lagoon located between mainland Florida and the Florida Keys. The Bay is the largest of the Park's marine systems and is recognized as critical fishery habitat supporting prominent south Florida fisheries. The Bay is considered to be the principal nursery ground for the Tortugas pink shrimp fishery. Hard bottom habitats serve as critical nursery habitat for the spiny lobster. The pink shrimp and spiny lobster fisheries are recognized as the two largest commercial fisheries in Florida. Florida Bay also supports an extensive recreational hook and line fishery which is critical to the economy of the Florida Keys.

In the fall of 1987, a widespread, rapid die-off of turtle grass (*Thalassia testudinum*) began in Florida Bay. Die-off occurred in areas of dense seagrass cover and, principally, in western Florida Bay. Apparently linked to the loss of seagrass cover, increasingly extensive and persistent turbidity and algal blooms, have characterized western and central Florida Bay since 1991. Abrupt changes of this magnitude have not been observed previously in Florida Bay nor have similar occurrences been reported in the scientific literature for other tropical seagrass systems. In Florida Bay these changes were hypothesized to threaten the bay's water quality, sport fishery, and nursery function. In the short-term, grass canopy loss and declining environmental conditions may lead to shifts in species composition and reduced abundance of grass canopy dependent organisms. Over a longer-term increasing seagrass habitat heterogeneity may result in enhanced secondary productivity.

Roughly coincident with these habitat changes in the bay have been declines in the offshore Tortugas pink shrimp fishery and a die-back of sponges, critical habitat for the spiny lobster (Nance, 1994; Butler and others, 1995). Within the bay, abundance and species composition of seagrass associated fish and invertebrates, including the pink shrimp, have been shown to be lower in areas of seagrass die-off when compared to adjacent undamaged or recovering seagrass habitats (Robblee and DiDomenico, 1992).

A detailed quantitative data base, initially developed by the National Park Service (NPS), has evolved since the early to mid-1980's prior to seagrass die-off describing prominent faunal elements (pink shrimp, caridean shrimp, and fish) characteristic of seagrass habitats in Johnson Key Basin in western Florida Bay. This data base has been expanded over time. The NPS added additional data between May 1989 and August 1991, a period following the advent of seagrass die-off in Johnson Key Basin but prior to the extensive and persistent plankton blooms which have characterized western and central Florida Bay since 1991. More recently, within a multiagency Decadal Comparison Program, data were added when the experimental design used originally between October 1984 and April 1987 was duplicated between October 1994 and April 1997. This was a multiagency program involving the

Florida Marine Research Institute; the National Marine Fisheries Service; and the U.S. Geological Survey, Biological Resources Division (Matheson and others, in press; Thayer and others, in press). Since April 1997, this project has continued routine sampling of long-term monitoring stations in Johnson Key Basin in order to extend this detailed biological record.

Distinct differences in the species composition of fish and caridean shrimp communities were evident in Johnson Key Basin in the mid-1990's when compared to the mid-1980's. Rainwater killifish (*Lucania parva*) and the caridean shrimp (*Thor floridanus*), once the most dominant communities in the seagrasses of Johnson Key Basin prior to seagrass die-off in 1985, decreased by over 62 and 93 percent, respectively, by 1995. However, other species increased in abundance--the code goby, *Gobiosoma robustum*, the bay anchovy (*Anchoa mitchilli*), and the burrowing caridean shrimp (*Alpheus herterochaelis*), were found in greater numbers in 1995. The appearance of the bay anchovy and also the Spanish sardine (*Sardinella aurita*), observed for the first time in throw trap collections in 1995, is thought to be in response to the persistent increase of algal blooms.

Funding for this research was provided from the U.S. Department of the Interior, South Florida Ecosystem Restoration Program "Critical Ecosystems Studies Initiative" (administered through the National Park Service); and, in part, from the U.S. Geological Survey, Florida Caribbean Science Center for the "Empirical and Modeling Studies in Support of Florida Bay Ecosystem Restoration Program."

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Relationships Among Inshore Sources of the Pink Shrimp, *Penaeus Duorarum*, and the Offshore Tortugas and Sanibel Fisheries

By Michael B. Robblee¹, Brian Fry², James W. Fourqurean³, and Patricia L. Mumford³

South Florida's seagrass and mangrove dominated estuaries serve prominently as nursery habitats for the pink shrimp (*Penaeus duorarum*), supporting both the Tortugas and Sanibel fisheries. The Tortugas pink shrimp fishery is the larger of the two and is the second largest commercial fishery in Florida with landings of approximately 9 million pounds annually prior to 1980. The Sanibel fishery is small by comparison averaging about 4 percent of the Tortugas catch annually. Early tagging studies suggested that western and southwestern Florida Bay, the middle Florida Keys, Whitewater Bay, Coot Bay, and the Ten Thousand Islands are nursery grounds supporting the Tortugas fishery; nursery areas for the Sanibel fishery are thought to include at least estuaries extending from Indian Key along the southwest coast of Florida to Pine Island Sound north of Fort Myers; and, juvenile shrimp in east coast estuaries (for example, Barnes Sound and Biscayne Bay) may not enter either fishery (Costello and Allen, 1966).

Linkages between inshore nursery grounds and offshore fishing grounds are complex and apparently poorly understood. Recruitment of pink shrimp into the offshore fishery occurs throughout the year with two peaks of recruitment; a fall recruitment period measured from July through December, peaking between August and October; and a spring recruitment period measured from January through June, peaking between March and May. The spring peak is larger than the fall and may be increasing. It is the fall peak that has declined during the 1980's in the Tortugas fishery. In contrast, available data on inshore abundance of juvenile pink shrimp in Florida Bay and Whitewater Bay suggests the prominence of single, late summer to early winter (August-December) peaks of abundance contributing to the spring peak on the offshore grounds (Costello and others, 1986; Robblee and others, 1991).

Questions regarding the relative importance of inshore nursery areas in south Florida and the timing of movements between inshore nurseries and offshore fishing grounds are considered critical for evaluating the cause of recent declines in Florida's pink shrimp fishery and for establishing the pink shrimp as a performance measure for evaluating restoration alternatives for Florida Bay. We are using natural stable C, N, and S isotope ratios to evaluate the relation between inshore shrimp stocks and offshore Tortugas and Sanibel fisheries. Stable isotopes have been used successfully as tracers to address similar questions in other shrimp populations, including south Florida (Fry, 1983). Shrimp assume isotopic signatures that reflect their nutritional base. The isotopic composition of the pink shrimp differs between seagrass and mangrove habitats as defined by $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ ratios (Harrigan and others, 1989). As shrimp migrate offshore, their isotopic composition gradually shifts with feeding and growth to reflect an open-water food web. Shrimp with different inshore isotopic compositions would tend to converge on open-water values with growth. Samples collected in the late 1970's show that young recruits to the Tortugas fishery have $\delta^{13}\text{C}$ values consistent with a recent past in seagrass meadows, such as those found in Florida Bay at that time (Fry, 1983).

Exploratory sampling was completed previously (Fry and others, 1997; Fry and others, in preparation). Based on these data, continuing efforts have been focused on Whitewater Bay/Ponce de Leon Bay and Johnson Key Basin in western Florida Bay. Sampling continues on both the Tortugas and Sanibel grounds with the assistance of Ed Little and Tom Herbert of the National Marine Fishery Service.

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Salinity Pattern in Florida Bay: A Synthesis

By Michael B. Robblee¹ and DeWitt T. Smith³

Salinity and its relation to climate and water management in south Florida is central to restoration activities in Florida Bay. Upstream water management over the last century has disrupted the quantity, quality, timing, and distribution of freshwater flows into Florida Bay which has subsequently affected salinity patterns. An assumed long-term trend toward increasing salinity in the bay and short-term effects of salinity (for example, hypersalinity and freshwater flooding) are integral elements of conceptual models of seagrass die-off. Loss of seagrass habitat beginning with seagrass die-off in 1987 is implicated in changes in sediment dynamics, nutrient dynamics, and nursery function that has characterized the bay over the last decade. Detailed paleoecological studies are underway to reconstruct salinity conditions in a “premanagement” Florida Bay as a possible restoration target. Hydrodynamic models (RMA10, FATHOM, SWIFT2D) are being developed for Florida Bay to aid in predicting circulation, inflow, and the movement of nutrients through the system. The water management system in south Florida is being evaluated and redesigned in the Central and South Florida Comprehensive Review Study. All these studies require salinity data and synthesis for calibration, verification, and interpretation. Despite these needs, present and past spatial and temporal patterns of salinity in Florida Bay have not been adequately summarized.

At this time, direct salinity observations from within Florida Bay extend from 1936 to the present. Anecdotal references to salinity conditions within the bay are known to exist from as early as 1908 within the scientific literature. The historic salinity data for the bay and adjacent waters have been compiled from all sources into a single data base, relating each observation to time and place. These data are useful, spatially and temporally, beginning in the mid-1950's, although significant gaps in both time and space are present. Everglades National Park has been monitoring salinity since 1981 at an increasing number of stations in Florida Bay. The Everglades National Park data base is temporally intensive and includes related rainfall and water-level data. Since 1995, bimonthly spatially intensive salinity surveys have been conducted by the U.S. Geological Survey within Florida Bay (Halley, 1996).

This project will combine these data sets, existing on different time and space scales, along with available anecdotal data, into a synthesis of salinity conditions within Florida Bay from 1900. During the first year, these data sets will be completed, quality analysis/quality checks will be performed, and a relational data base—including other relevant physical data (rainfall, evaporation, flow, etc.)—searchable by time, location and depth will be established. During the second year, a synthesis of salinity patterns in the bay, including a relation between salinity and freshwater inflow/rainfall, will be completed using this relational data base.

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Analysis of Sheet Flows to Florida Bay from C-111 Canal

By Raymond W. Schaffranek¹

Construction features of the Central and Southern Florida Project are suspected of contributing to the development of hypersaline conditions in nearshore embayments of central and northeastern Florida Bay as a result of diminished freshwater deliveries from the Taylor Slough and Canal C-111 drainage basins. Recent modifications in the C-111 project of the U.S. Army Corps of Engineers Central and Southern Florida Comprehensive Project Review Study (RESTUDY) include removal of 54 residual spoil mounds along the southwest bank of the canal to enhance sheet flow through the Everglades National Park (ENP) wetland and into Florida Bay. The wetland due south of C-111 in the “panhandle” area of ENP is of particular concern to current environmental restoration efforts because it constitutes a primary pathway for freshwater to reach nearshore embayments. Strategic operation of two hydraulic control structures, S-18C and S-197, at the endpoints of this 10.5-km segment of the C-111 canal can generate and(or) moderate canal to wetland flow exchanges and thereby regulate the magnitude and duration of sheet flow to Florida Bay. The objectives of this project, which is focused on the interconnected C-111 canal and wetland system, are to design, develop, and test data-collection and analytical methods to quantify the flow exchanges between the canal and the adjacent wetlands. The purposes of the research are to devise and demonstrate new methods by which to assess the effectiveness of implemented restoration actions and to develop improved models to simulate and evaluate new operational management strategies.

In September 1997, near the conclusion of the approximately 18-month-long spoil-removal effort, extensive flow measurements were made along the C-111 canal bank, the degraded spoil area, and the adjacent wetland. These data are being used to quantify and analyze canal and wetland flow exchanges, to evaluate the magnitude and extent of enhanced sheet flow into the wetlands, to develop an improved technique and approach to simulate such flow interactions, and to investigate the effect of recent construction modifications on flow-pattern and hydroperiod changes. Flow measurements were made in the 8.5-km segment of the C-111 overbank area that begins 1.5 km downstream of S-18C and ends 0.5 km upstream of S-197. Data were collected along nine transect lines perpendicular to the canal, spaced approximately 1 km apart, beginning at the southwest bank and extending about 1.5 km into the adjacent wetlands. Flow-velocity measurements were made at the canal bank, at the edge of the degraded spoil area, and at variably spaced intervals into the wetlands along the transect lines. Flow velocities were measured using portable acoustic Doppler velocity meters that have a resolution of 0.1 mm/s. The meters were retrofitted with internal electronic compasses and tilt sensors to provide flow directions that are geodetically referenced to Earth coordinates. Velocities were measured for 2 minutes, using a sampling rate of 10 Hz, at each of three points in the water column (0.2, 0.5, and 0.8 depths) for depths greater than 15 cm. For shallower depths, a 2-minute velocity measurement was made only at middepth.

Inspection of these multiple sets of velocity data revealed a south to south-southwest sheet flow primarily toward the eastern segment of Joe Bay and the western segment of Long Sound in the northeastern corner of Florida Bay. Measured flow velocities were typically on the order of 1 cm/s or less in the wetlands, and flow depths averaged about 30 cm. Velocities were generally greater in deeper areas having less dense vegetation, which verifies that flows typically follow paths of least resistance. Further analyses of these data are currently underway to determine the extent and patterns

of sheet flow and to evaluate their correlation with concurrent flows through the control structures. Depth-integrated unit-flow discharges are being computed at the velocity-measurement sites from which mass fluxes through transect lines in the wetlands can be calculated. These computed fluxes in the wetland will be compared with flow discharges measured at three fixed acoustic velocity-meter installations in the canal to determine and contrast the quantity of water conveyed in the canal with that transferred to the wetland.

In a separate and related data-collection effort, flow velocities were measured along three transect lines beginning near the midpoint of the 8.5-km canal segment and extending approximately 2.3 km into the wetland. Flow measurements were made in the center and about 150 m on both sides of an established airboat trail that traverses the wetland southward from the canal. Vegetation within this and other established airboat trails in the area is substantially compressed and presents less biomass throughout the water column than does vegetation in the surrounding undisturbed wetland. Inspection of these data indicated that flow velocities in the airboat trail were consistently equal to or greater than those in the adjacent wetland. Although velocity differences were small, these findings serve to substantiate the role that vegetation plays in exerting resistance to flow. Additional research and focused data-collection efforts are needed to evaluate the significance and to quantify the effects of established airboat trails on flows and drainage within the wetland south of C-111. A number of such established trails are clearly shown in aerial photographs, including a major trail that parallels the east-west boundary of ENP and presents a conduit to potentially channel sheet flow toward the east and away from nearshore embayments in central Florida Bay. These preliminary analyses indicate that in hydraulically sensitive environments, such as the Everglades, even the most subtle alterations to the natural system can have lasting residual effects on flow patterns and resulting hydroperiods.

Investigation and simulation of canal and wetland flow interactions require basic data of finer resolution and greater accuracy than that required for evaluation of regional-scale processes. In this regard, continuing project efforts are focused on collection of additional sets of refined data that are needed to quantify canal/wetland flow exchanges and to test new numerical algorithms and model improvements. These data-collection efforts include measuring a wider range of canal and wetland-flow conditions, surveying the degraded spoil area and adjoining wetland-surface elevations at a finer resolution and to a greater accuracy, and improving characterization of the wetland vegetation for better definition and treatment of spatially variable flow-resistance effects. Collection and interpretation of these basic data, and subsequent findings derived from models built on them, support the development of improved techniques to formulate plans and to evaluate restoration actions for preservation of the ecosystem, lead to the development of better tools for managers to assess changes in the ecosystem in response to imposed alterations, and to enhance understanding of the consequences of human interventions on the ecosystem.

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Hydrologic Variation and Ecological Processes in the Mangrove Forests of South Florida

By Thomas J. Smith III¹, Gordon H. Anderson², William K. Nuttle³, James E. Saiers⁴

The mangrove-dominated coastline of the southwestern Everglades is a complex maze of small and large islands which are highly dissected by small streams and large tidal river channels (Wanless and others, 1994). The surface sheetflow, typical of the central and southern Everglades, slowly becomes channelized, first in small streams and then in larger, tidally dominated rivers as one nears the coast. Tidal influence can be detected for considerable distances from the river mouths. On the Shark River for instance, a tidal signature is present at Everglades National Park gauge P35, some 35 km upstream from the mouth of the river. Ground-water dynamics in this land-margin ecosystem are very poorly understood.

Beginning in 1993, a series of ground- and surface-water monitoring wells was established in a series of five transects across the freshwater marsh mangrove forest interface of Everglades National Park (ENP) as part of the South Florida Global Climate Change Program. Three transects are in the mangroves of the southwest coast of ENP. These run along the Shark, Lostmans, and Chatham Rivers. On each transect there is an upstream well located in a freshwater marsh setting; a midstream well located in a brackish marsh/mangrove forest ecotonal setting; and a downstream well located in a pure mangrove forest near the river's mouth. On the Shark and Lostmans Rivers, lateral transects were also established to permit sampling near the river's edge and in the interior of the large coastal islands. These island interior environments are usually dominated by brackish marsh vegetation. Two transects were located downstream of the C-111 canal in the "panhandle" region of ENP. These transects are on Highway Creek and Joe Creek.

At present, the sites are instrumented with surface, soil and ground-water wells to record water-elevation data. Conductivity measurements are made at a number of well locations. The sites are radio-telemetered to allow daily access and checking of operational status of the site. Data are quality analysis/quality checked on a regular basis and are currently archived at ENP. Vegetation plots have been established at most sites (see Smith & Whelan, this volume) so that ecological processes (for example, primary productivity) can be related to the hydrological information gathered. A report detailing the first year of data acquisition (water year 1997) is in final stages of production (Anderson and others, 1999).

Data from the project are currently being used for two analyses of direct interest to resource managers in south Florida: (1) to examine the hydrological impacts of the passages of Hurricane Georges and Tropical Storm Mitch on the rivers of the southwestern coast of ENP; and, (2) to look at the hydrological impact of the removal of the levee along the south side of the C-111 canal and ask the simple but important question: Did removal of the C-111 levee improve the hydrology south of the canal? These analyses will be completed within the next several months.

Finally, this network of hydrological monitoring stations is uniquely suited for measuring the impacts of the south Florida ecosystem restoration on the downstream mangrove forested wetlands of the Everglades.

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Vegetation Dynamics in the Land-Margin Ecosystems: The Mangroves of South Florida

By Thomas J. Smith III¹ and Kevin R.T. Whelan²

Mangrove forests dominate the land-margin ecosystems of the southwestern Everglades. Over 100,000 ha are found in this region (Odum and McIvor, 1990). Mangroves provide considerable goods and services to mankind including: production of commercially and recreationally important fisheries, shoreline stabilization and protection from storm surges, and the improvement of water quality by uptake of nutrients (Ewel and others, 1998). Within the greater South Florida ecosystem, mangrove forests are at the downstream end of the vast “River of Grass” and thus are at the receiving end of upstream water-management decisions (Smith and others, 1989).

In addition to receiving freshwater from upstream sources, mangroves are subjected to periodic catastrophic disturbances, such as Hurricane Andrew, sea-level rise, and occasional freeze events. Significant research activities to understand the ecology of mangroves commenced following the passage of Hurricane Andrew (Smith and others, 1994).

A network of permanent vegetation sampling plots was initially established throughout the mangrove forests along the southwestern coast of Everglades National Park. Plots were located on the upstream downstream gradients of the Shark, Harney, Broad, and Lostmans Rivers in the fall of 1992 and spring of 1993. Subsequently, additional plots were established in the 10,000 Islands National Wildlife Refuge, Rookery Bay National Estuarine Research Reserve, and on the islands and northern shoreline of Florida Bay in Everglades National Park. In many cases, plots have been collocated with sites of other research activity, such as in the vicinity of the surface- and ground-water sampling wells of the South Florida Global Climate Change Program (see Smith, Anderson, Nuttle, this volume). Additionally, a sediment elevation table network is being established at these sites to measure important sedimentological processes (see Cahoon and Smith, this volume).

The plots are circular with a permanent center marker. Every stem over 1.4 meters in height is identified to species and its “diameter at breast height” (dbh) measured. All stems were permanently tagged and the compass bearing and distance from the center stake to each stem recorded. The initial surveys estimated stem damage and tree death caused by Hurricane Andrew. Subsequent surveys have recorded growth (as change in dbh), death and new stems. Also, with each resurvey, the cause of death is recorded if possible (that is, Hurricane Georges in 1998). Sediment porewater chemical parameters (nitrogen, phosphorus, sulfide, and salinity) were measured in a subset of the plots during 1994-95.

The initial surveys revealed catastrophic mortality (100 percent in some cases) from Hurricane Andrew (Smith and others, 1994, Doyle and others, 1995) especially in areas crossed by the eye of the storm. Resurveys over the past 7 years have revealed complex patterns of regrowth and recruitment of new individuals into the forest. The white mangrove (*Laguncularia racemosa*) has dominated recruitment at many, but not all, plots. Both the red mangrove (*Rhizophora mangle*) and the black mangrove (*Avicennia germinans*) have recruited heavily into some plots. Both recruitment and growth showed little correlation with the soil chemical parameters tested to date.

The most upstream plots, those nearest the freshwater Everglades had little damage from Hurricane Andrew, primarily because the trees in these plots are much shorter than trees in downstream plots. However, it is these upstream plots which should exhibit the first measurable changes (for example, growth) to the water-management scenario proposed as part of the south Florida ecosystem restoration. Our mangrove forest permanent plot network is ideally suited for measuring change associated with the hydrological restoration of the Everglades.

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Long-term Experimental Study of Fire Regimes in South Florida Pinelands

By James R. Snyder¹

A history of lightning- and human-caused fire in South Florida has resulted in fire-dependent ecosystems over most of the area. Much of the remaining natural area is public land subject to wildland fire, with the National Park Service (NPS) managing over 4,000 km² of Federal land in Everglades National Park and Big Cypress National Preserve. Other U.S. Department of the Interior units with fire-maintained vegetation include the National Key Deer Refuge, Florida Panther National Wildlife Refuge, and Loxahatchee National Wildlife Refuge. Fire management, both wildfire suppression and prescribed fire, is a major natural-resource management activity throughout the area. The oldest prescribed fire program in the NPS began in Everglades National Park in 1958 and, today, the majority of prescribed fire conducted by the NPS is in South Florida. Big Cypress National Preserve has developed the largest management-ignited prescribed fire program in the NPS, often burning more than 15,000 ha (35,000 acres) in a year.

Fire plays an important role in controlling the distribution and composition of plant communities in South Florida. Some 65 vascular plant taxa are endemic to southern Florida; more than half are herbs and low shrubs restricted to pine forests. These species are quickly shaded out in the absence of fire. Lightning is assumed to have been an important source of fire ignitions throughout the evolution of the South Florida landscape, although humans have been influencing the fire regime for thousands of years. However, in the last several decades increased human intervention in the form of hydrologic alterations, creation of artificial firebreaks (such as roads and canals), fire suppression, and intentional and accidental ignitions has severely disrupted the natural fire regime. In fact, next to hydrological modifications, alteration of the fire regime is one of the most pervasive impacts of humans on the South Florida ecosystem.

The main objective of this study is to establish the baseline conditions and begin the experimental treatments for a long-term study of season and frequency of burning in South Florida pinelands. The long-term study will document the ecological effects of a wide range of potential fire-management strategies (Snyder 1991). The research will provide detailed data on vegetation responses to different burning regimes that will be considered along with wildlife, public safety, and other management concerns in refining prescribed burning programs on Interior lands in South Florida. Specific objectives for the initial phase include: (1) describing the vascular plant communities of all treatment units to document initial conditions, (2) conducting all the initial experimental burning treatments, and (3) documenting the short-term effects (<1 year) of season of burning and fire intensity on selected vegetation parameters.

The experimental study has been set up in eastern Big Cypress National Preserve, where the only extensive unlogged stands of South Florida slash pine (*Pinus elliottii* var. *densa*) remain. The pinelands exist as a mosaic of small, slightly elevated “islands” within a matrix of cypress domes and dwarf cypress prairies. The substrate is a shallow layer of sand over limestone bedrock, making these pinelands transitional between the true rockland pine forests of the Miami Rock Ridge and the widespread pine flatwoods to the north. The study site of 2,573 ha surrounds the Raccoon Point oil field and is divided into 18 experimental burn units each containing at least 50 ha of pine forest.

Each burn unit contains three 1.0 ha tree plots in which all trees with diameter at breast height (dbh) >5.0 cm are tagged and mapped. Smaller 0.1 ha vegetation plots are located in the center of each tree plot and at two additional locations to sample herbaceous and shrubby vegetation. There are a total of 54 tree plots and 90 vegetation plots. The tree plots (containing a total of 16,370 trees) show the Raccoon Point pinelands to have average stand densities (trees/ha) of 227 pines, 53 cabbage palms, and 24 cypress.

The experimental design consists of burning at three seasons (spring, summer, winter) and two frequencies (every 3 years and every 6 years) for a total of six treatment combinations. Each treatment is replicated three times, with one replicate being burned per year for 3 years. The project is a cooperative effort of the USGS and the NPS and all the experimental prescribed burns are conducted by the Big Cypress National Preserve Fire Management Division. Beginning in June (spring) 1996, two units have been burned at each season, representing both short and long frequency treatments. By spring 1999 all 18 of the initial experimental prescribed burns will have been completed and the second cycle of burns of the 3-year treatments will begin.

Over the next 3 years, while the short-frequency burn treatment units are being burned for the second time, vegetation plots will be resampled to detect effects of season of burning. In addition, short-term responses to season of burning, such as the survival and establishment of pine seedlings and the flowering and fruiting of selected herbaceous species (for example, pineland clustervine (Spier and Snyder, 1998)) will be documented.

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Methods for Quantifying Ground-Water Seepage Beneath Levee 31N, Miami-Dade County, Florida

By Helena Solo-Gabriele, Ph.D.¹ and Mark Nemeth²

Subsurface seepage across the eastern boundary of the Everglades in southern Florida is controlled, in part, by a levee and canal system, which was constructed to maintain sheetflow conditions within the Everglades and prevent flooding in urban areas. Because of water-level differences between these areas, a relatively steep hydraulic gradient exists across the levee system, which, coupled with a highly permeable aquifer, causes considerable subsurface flows. Recognizing the potential magnitude and importance of subsurface seepage across the levees, the U.S. Geological Survey (USGS) in conjunction with other Federal, State, and local agencies and Indian tribes, has included the quantification of subsurface seepage as one of the objectives of the USGS South Florida Ecosystem Program.

The purpose of a recent study conducted by the USGS, as part of the South Florida Ecosystem Program, was to develop a fully integrated model in the vicinity of Levee 31N capable of simulating three-dimensional ground-water flow in the Biscayne aquifer combined with surface-water routing capabilities for the L-31N Canal. The modeling results were utilized to quantify seepage rates below Levee 31N and to develop an algorithm suitable for providing real-time estimates of seepage through and below the L-31N canal. The study site encompasses a 110-square kilometer area along Levee 31N and includes part of the East Everglades and the western extent of suburban Miami-Dade County. The eastern and western portions of the site are separated by Levee 31N and its adjacent canal (L-31N). The northeastern part of Everglades National Park (ENP), including the eastern edge of Northeast Shark River Slough, is on the western part of the study site. The eastern part of the study site includes lakes created by rock-mining activities, three municipal pumping wells (combined pumping rate of 0.66 cubic meter per second), and urban development. Immediately underlying the land surface is the Biscayne aquifer, which is characterized by hydraulic conductivities that generally exceed 3,000 meters per day and transmissivities of about 90,000 square meters per day. Throughout most of the site, the ground-water table is at a depth of 1 to 2 meters below land surface, and the L-31N canal intersects the upper part of the aquifer, permitting a direct hydraulic connection.

Model development for the study included gathering data for input and calibration. Supplementary data collected as part of this study included direct measurements of seepage within ENP, lithologic information obtained from two new geologic cores, and data collected from the operation of newly installed monitoring wells. Results from seepage meter tests indicate that vertical seepage rates are dependent upon vertical and horizontal hydraulic gradients and increase within the Everglades nearer to the levee. The geologic cores collected in the Everglades, along with data collected from other sources, reveal the presence of two semiconfining layers below the study site. These layers were incorporated into the model.

The numerical model utilized for simulation purposes was a modified version of MODBRANCH. MODBRANCH couples a quasi-three-dimensional ground-water flow model, MODFLOW, with a one-dimensional surface-water routing model, BRANCH. Modifications to the MODBRANCH code focused on changing the original relation used to model leakage between the surface-water and ground-water systems to one referred to herein as the “reach-transmissivity” relation. The performance of the modified version of the code has been verified using relatively simple runs with known solutions as well as by comparison to results from the original version of

MODBRANCH for more complex scenarios. The numerical model results were used to develop an applied real-time seepage algorithm, which is an algebraic relation based theoretically on the reach transmissivity equation incorporated into the modified MODBRANCH routine. Leakage estimates using the algorithm require only aquifer heads, and the algorithm can be used with real-time monitoring data to provide estimates for seepage along Levee 31N.

Results of the study are of significance to water managers and those involved in Everglades restoration efforts. For example, seepage estimates provided by the South Florida Water Management Model (SFWMM), which is used by local water managers to determine the effect of canal operations on water levels throughout southern Florida, can be checked with the results of this study. The current seepage algorithm used by the SFWMM is a regression relation that was empirically derived through comparisons with a two-dimensional ground-water flow model. The new algorithm developed through this study is physically based.

Results of this study also are necessary for developing a water balance for the northeastern part of ENP, an area which is targeted for future restoration efforts. Water deliveries to the area will likely change in the near future to affect a change in water levels. The model developed through this study can be used to estimate the impact of water-level changes on subsurface seepage rates below Levee 31N, and water deliveries to the area can be adjusted accordingly with respect to seepage losses. Additionally, subsurface outflows from ENP replenish a part of the Biscayne aquifer which underlies urban areas. During dry periods, the aquifer is at risk of saltwater intrusion near the coast, induced by limited inflows and municipal well-field pumpage. During wet periods, urban areas are prone to flooding which can be aggravated by excessive subsurface flows from the Everglades eastward. Maintaining acceptable water levels in urban areas requires quantifying and ultimately controlling subsurface flows below the levee system. An accurate estimate of the transfer of water across the Everglades boundary is, therefore, crucial for water management in urban areas. The model also can be used to evaluate the potential effects of proposed expansion of rock-mining activities and municipal well-field pumpage immediately east of Levee 31N on seepage rates below Levee 31N and, ultimately, the water balance of the East Everglades.

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Two-Dimensional Simulation of Flow and Transport to Florida Bay Through the Southern Inland and Coastal Systems (SICS)

By Eric D. Swain, Ph.D.¹

The system process studies of the southern Everglades area have been integrated into a two-dimensional numerical model of surface-water flow through the wetlands and into Florida Bay. The model chosen for this task is the Surface-Water Integrated Flow and Transport in Two Dimensions (SWIFT2D) code. The SWIFT2D model numerically solves finite-difference forms of the vertically integrated mass and momentum conservation equations in conjunction with heat, salt, and constituent flux transport equations. An equation of state for salt balance is included in the model to account for pressure gradients that result from density variations. Thus, the hydrodynamic and transport computations are directly coupled. Information on ground-water and surface-water elevations, rainfall, evapotranspiration, frictional resistance terms, boundary water levels and flows, wetland flow velocities, ground-water inflows, and wind-frictional terms are all derived from the process studies and incorporated into the model. The model serves to synthesize the results of the process studies into an integrated dynamic representation of the hydrologic regime.

For initial calibration and testing, a 2-month (July-August 1997) simulation period was used. This period coincided with field-measured flow velocities in the wetland and at model boundaries. The field data that are most significant for model comparison are the continuous discharge measurements made at five coastal creeks. The topographic high along the coast, referred to as the Buttonwood Embankment, acts as a major hydraulic control, and the creek flows are a good indication of the behavior of the system. Because field research of controlling system processes yields most of the input data, the calibration parameters are kept to a minimum which allows for more confidence in simulation results.

The comparison of simulated creek flows with and without the effects of wind highlighted the importance of wind-forcing effects on water movement. Frequent flow reversals (inland direction) measured in the creeks could not be simulated without incorporating wind into the model. Using field-measured wind speed and direction in the model, these reversals were well simulated. However, wind-driven water-level fluctuations in Florida Bay are not the primary driving force in flow reversals. Simulating the measured water-level fluctuations in the bay without wind-forcing effects on the inland wetlands does not represent the flow reversals.

With the exception of the deeper parts of Taylor Slough, surface-water flow in the wetlands can be induced to move in any direction by the wind. Flow direction varies so rapidly that model-generated, daily flow-velocity averages cannot be compared with field measurements taken over a period of several minutes. However, model-generated and field unit discharge values (average velocity times depth) that are simultaneous coincide well. Both simulated and field-measured data record episodes when southward flow in the deeper parts of Taylor Slough occurs simultaneously with wind-driven flow to the north in adjacent shallow wetlands.

The flat, slow-flowing wetlands of the Everglades have very low gradients; the largest water-level gradients and the major processes which control flow occur at the coast. Water-level gradients tend to be on the order of 0.15 foot per mile in the inland wetlands, but simulated coastal gradients are, at times, 0.5 foot per mile. This observation is supported by specific coastal creek water-level measurements. The topographic high (Buttonwood Embankment) found along much of the coast is the most important flow control in the system, usually confining flow to the coastal creeks.

During wetter periods, the salinity of Joe Bay and the other subembayments is negligible, and a sharp salinity gradient exists offshore. Despite periodic wind-induced flow reversals, saline water is flushed from inland areas during wet periods. During dry periods, salinity in the Seven Palms Lake area and Joe Bay can be significant.

A 7-month period (August 1996 to February 1997) was simulated to establish coastal boundary conditions to aid U.S. Army Corps of Engineers hydrologic models. For the most part, this extended simulation period used the same input parameters as the shorter simulation. One important difference is the replacement of the northern flow boundary at Taylor Slough Bridge with a water-level boundary, largely due to a lack of flow data for the 7-month period.

The 7-month simulation allows quantification of the long-term effects of wind on total flow at the coast. Although the short-term effects can be dramatic, the net effect on cumulative flow volumes required a separate analysis. At the largest outflow point, Trout Creek, simulated flow volumes were 18 percent lower when the effects of wind are considered. Measured and simulated flow volumes with the effects of wind were within 6 percent of each other, so the wind differences can be considered significant. At lower outflow points, such as Taylor Creek, wind may not have notable effects on flow; differences were less than 2 percent. Trout Creek has a deeper water area upstream, Joe Bay, within which the seiche probably accounts for the higher sensitivity of flow to wind.

An analysis of the short- and long-term simulations suggests that the upper part of Taylor Slough flows southwesterly, but the water generally proceeds southeasterly from the lower slough toward the Joe Bay area. The West Lake/Seven Palms Lake area, which appears to be in-line with the southwesterly orientation of Taylor Slough, actually receives less water from the slough than Joe Bay. This is due to relatively high topography north of the Lakes area and a higher hydraulic gradient occurring between Taylor Slough and Joe Bay. The West Lake/Seven Palms Lake surface-water flows are nearly cut off from Taylor Slough during dryer periods, as has been confirmed by measured flows at the coastal creeks.

The SICS model is a useful tool for understanding the effects of processes controlling the coastal hydrology of Florida Bay and for defining boundary conditions of other models. This model is currently being expanded to include adjacent areas and to further refine the model process.

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Population Structure and Spatial Delineation of Consumer Communities in the Everglades National Park

By Joel C. Trexler¹, Karen Kandl¹, and William F. Loftus²

Restoration activities in the Everglades will include alteration of the present system of levees and canals, flow patterns, and hydrological dynamics of the ecosystem. The effect of these ecosystem changes on aquatic animals will, in part, be dictated by their patterns of movement and dispersal at present and in response to change. However, prior to this research, there existed little foundation of knowledge of aquatic animal population structure and dispersal patterns. In modeling the dynamics of aquatic animal populations in southern Florida wetlands, it has become apparent that the dispersal distances, rates of movements, and timing of movement are important but poorly understood. Migration is a critical parameter for understanding the response of organisms to environmental change. Migration rate and pattern can be examined using direct or indirect techniques. For animals, direct methods generally involve following the movements of marked individuals. Indirect methods include examination of patterns of genetic diversity and patterns of stable-isotopic markers. The small size of most of the wetland animals precludes the use of standard marking techniques for studying movement, and the large, open system of these wetlands makes recapturing marked animals improbable. Likewise, the short lifespans of these animals makes recapture difficult. Use of genetic markers in determining the presence of structure in populations offers an indirect way of assessing the degree of movement and mixing in these populations, and a cost-effective approach to examine landscape-level patterns of animal movement.

Populations of a given species that do not frequently interbreed and exchange genetic information will show larger differences in allele frequencies than two populations that often interbreed. When many populations are sampled spatially, the genetic signatures of the populations provide information on the degree and frequency of interbreeding and, therefore, dispersal. Mathematical algorithms have been developed to estimate migration rate from such data, given known assumptions. The analyses proposed use already proven methods of assessment that employ allozymes and DNA.

In this series of studies, our objectives are to identify population structure of selected aquatic species in the Everglades, estimate migration rate from genetic data on gene flow for incorporation in the "Across Trophic Level System Simulation" (ATLSS) model, and to test the hypothesis that levee and canal systems act as barriers to dispersal of aquatic animals in the Everglades. Future funding will support the expansion of this line of study by incorporating: (1) the use of DNA markers to study the genetic relationships of common Everglades aquatic animals; (2) the continued use of allozyme analyses with additional species; and (3) the physical tagging and marking of large and small animal species to directly measure movement, dispersal distance and seasonality, and residency in refuges. DNA analyses will expand the resolution of genetic analysis provided by allozymes. The scale of population isolation, and thus migration, resolvable by genetic markers depends on their rate of mutation and microevolutionary change. DNA markers can be identified with mutation rates covering a wider range than allozymic markers. In this case, DNA markers that evolve at as rapid a rate as possible to produce DNA fingerprints will be used to compare different regions of the Everglades, and across water-management structures.

The research to date has focused on the mosquitofish (*Gambusia holbrooki*), grass shrimp (*Palaemonetes paludosus*), and spotted sunfish (*Lepomis punctatus*). Our future plans include studies involving crayfish and large-bodied fish that inhabit alligator ponds. We will use mark-recapture-release techniques for large-bodied species at alligator holes for comparisons of dispersal results with estimates of population structure from genetic data. An important data gap in the system is information on the inter- and intra-annual variability in large-bodied fish populations in the wetlands. An ongoing U.S. Army Corps of Engineers-funded project is now examining seasonal changes in the use of marshes and ponds by large fishes. Tagging the fishes in ponds followed by recapture attempts in the ponds and nearby marshes would provide data on relative habitat use, population size estimates, and habitat fidelity. Similarly, at critical times of dry-down, marking large numbers of small fishes as they enter refuges will give the data needed to determine the effects of predation by larger fishes on survival and mortality of those numerically dominant species. Those data will directly support other ongoing and proposed studies of aquatic animals in the Rocky Glades, in alligator holes and headwater creeks, and in the Big Cypress Swamp. The data are essential to refine and test the ATLSS fish model.

With 1997 funding, we made 2 years of field collections of mosquitofish, grass shrimp, and spotted sunfish. Over 50 populations each of mosquitofish and shrimp, and 25 of spotted sunfish, were analyzed in 1996-97. The examination of changes in allele frequencies across generations at a particular location provides additional information about population demography. In 1997, a subset of those populations was resampled to compare interyear estimates of genetic variability. A paper describing the results of these efforts is in the peer-review process. We found clear evidence that water-management units (Shark River Slough, Taylor Slough, Water Conservation Areas-3B and -3A) display different patterns of genetic diversity in mosquitofish and possibly spotted sunfish. This indicates that the levees and canals separating them are acting both as barriers to mixing, and create unique hydrological environments within the management units that influence the population dynamics of mosquitofish differently. For example, genetic diversity is quite low for mosquitofish in Water Conservation Area-3B, which is isolated from adjacent canals by levees. This suggests that fish populations there have gone through a severe reduction in population size in the recent past, and experience little or no mixing from nearby areas. Mosquitofish from canals have consistently high levels of genetic diversity compared to nearby marshes, indicating that canals are sites of genetic interchange for this species. There was no evidence for structure in populations of grass shrimp.

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Experimental Studies of Predator and Prey Interactions

Joel C. Trexler¹, William F. Loftus², and Sue Perry³

Certain studies needed to understand the fish community are difficult to carry out in the field, yet require more space than the confines of laboratory aquaria. Mesocosm experiments provide information on feedback mechanisms among trophic levels in food webs that can play a central role in efforts to model community dynamics. These effects would be very difficult to identify in typical correlative field studies. An experimental mesocosm constructed in Everglades National Park allows us to address questions of predator-prey, competitive, and indirect interactions. The mesocosm is also suited to address questions about the role of nutrient inputs into the Everglades in causing shifts in marsh food webs. The mesocosm also provides the opportunity to examine introduced/native fish interactions, and to test potential control methods.

One of the primary unknowns for modeling the dynamics of fish communities in the Everglades is the identification of factors that limit population growth and community dynamics. Two hypotheses are now debated in the literature regarding the limitation of population dynamics of small-bodied species: (1) that predator-prey interactions limit the population growth, or (2) that food limitation sets bounds on the size of populations. The mesocosm will complement field studies by providing opportunities for experimental studies under more controlled conditions than possible in field conditions, but at a larger scale and with more fieldlike conditions than in laboratory aquaria.

Three types of studies are planned for the mesocosms on the 5-year horizon projected for this funding. They are the study of (1) intraguild predation with mosquitofish, (2) the effects of predation by mosquitofish and bluefin killifish on nesting successes of sunfish, and (3) the effects of nutrient level and primary production on population growth of small-sized fish. Those projects are described in the original proposal. Their results will fit closely with completed and continuing research describing Everglades aquatic communities through field sampling, planned field caging studies on grazing ecology along hydrological gradients, and field nutrient manipulation in the dosing flumes. The ultimate goal of this research is to develop a model of ecological regulation across trophic levels for Everglades environments. Our first experiment examines size-structured predator-prey and competitive interactions involving mosquitofish, sailfin molly, and bluefin killifish. We selected this experiment for two reasons: (1) it will provide important information about trophic interactions for the "Across Trophic Level System Simulation" (ATLSS) model, and (2) it will permit us to work out logistical issues for conducting experiments in the mesocosms while gathering useful data. Mosquitofish were chosen as the focus of our first experiment because they are ubiquitous, and are notorious as a predator of larval and juvenile fish and invertebrates. Mosquitofish are omnivores, and so may regulate the growth of periphyton directly, or influence it indirectly by feeding on other grazers. Mosquitofish may also regulate their abundance somewhat through cannibalism. These interrelationships need to be incorporated in a fish communitywide ATLSS model.

Most of this first study has been completed and the preliminary analyses revealed the strong effects that mosquitofish may have on fish community regulation in the Everglades. We demonstrated that this facility will be successful in performing complex factorial experiments. The results showed that sailfin molly and bluefin killifish adults do not prey on juvenile fish, but mosquitofish exert strong predatory influence on small specimens. Because of its abundance in the marsh, mosquitofish may perform a regulatory role on the small-fish assemblage. The experiment also showed that food limitation might affect population dynamics in the community. Slower growth of juvenile fish because of shared food resources may slow growth and increase predation risk.

Sunfish nesting mortality: The next experiment that we are beginning examines the potential effect of small-fish predation on nests and larvae of sunfishes. Preliminary data indicate that sunfish nesting in Everglades National Park experience different rates of nest predation depending on water depth. The hard substrates needed for nesting are limited in there and, so, sunfish nest in approximately the same areas each year. The depth of water at the nesting sites is a function of the rainfall that year. In years of low water, the surface dwelling mosquitofish occur in near proximity to the sunfish nests. At such times, the number of nest attacks per unit time increases, causing the male nest guarder to spend more time chasing predators away (Loftus, personal observation). We have begun by having a graduate student learn how to breed and raise the sunfish in captivity. We will explore how water depth affects nesting success by examining nesting success of spotted sunfish in tanks, with mosquito fish, bluefin killifish, and juvenile sunfishes as potential predators, at different water depths. We will census the number of eggs per nest, number of larvae hatched, and number of juveniles produced. Each tank will be set up with standardized periphyton cover and invertebrate communities such that alternative prey for mosquitofish is present, as in natural conditions. Additionally, we will perform nest observations in the field to estimate predation rates there at different water depths.

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Network Analysis of Trophic Dynamics in South Florida Ecosystems

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This project aims to quantify the networks of trophic interactions that occur among the major taxonomic groups of the various Everglades habitats. The strategy is to use available information on levels of biomass and exchanges of carbon to piece together complete budgets for each ecosystem. Typically, this exercise results in a “tangle” or “bird’s nest” of interactions that requires systematic analysis. The structural characteristics imbedded within these complicated pictures are revealed through application of a suite of algorithms collectively referred to as “Network Analysis.”

Network Analysis was developed largely by the principal investigator, and can be used to reveal how each member of the ecosystem contributes to, and is dependent upon, each of the others. It also portrays the trophic “spectrum” of each participant (that is, the degrees to which each functions at the various trophic levels--autotroph, herbivore, carnivore, etc.). It depicts as well the trophic spectrum of the system as a whole. Furthermore, the analysis identifies and enumerates the manifold pathways for recycle within the system and constructs from them the composite structure for recycle in the system as a whole. Finally, the algorithms provide a set of indices grounded in information theory and thermodynamics that describe the activity level and organization of the system as a whole.

These products in concert provide investigators with a didactic image of how the ecosystem is functioning that is part of the overall package of models of the “Across Trophic Level System Simulation” (ATLSS) program, but that is independent of ATLSS simulation activities, so that it can be used to keep check on the reality of predictions from these latter activities. Working the other way around, the outputs from ATLSS can be used to construct trophic networks at particular times and places. The analysis of networks thus synthesized should provide a significant, if not essential, tool for tracing the causal roots that underlie ATLSS predictions of community responses to changing water and/or nutrient levels. Network Analysis for two components of the Everglades/Big Cypress region has been performed so far, the cypress wetland ecosystem and the Florida Bay ecosystem.

The cypress wetland ecosystem: A 68-compartment budget of the carbon exchanges occurring during the wet and dry seasons in the cypress wetlands of South Florida has been assembled. These networks of exchange will serve as independent benchmarks against which the performance of the ATLSS multimodel, now under construction, will be assessed. During the construction of these networks, it soon became clear that the perceived fact—that these systems are driven by cypress litterfall—is simply not true. Less than half the carbon reaching the higher trophic levels has spent any time in the form of detritus. Production by the understory of vines, epiphytes, and aquatic vegetation play the key roles in sustaining the ecosystem, and phytoplankton is especially important during the dry season. The middle trophic level fish and amphibians appear to exhibit the highest trophic efficiencies found in the cypress ecosystem. Taxa at either end of the trophic chain appear to be less efficient by comparison. The result is a peak in efficiency at trophic level four. The trophic levels of most taxa do not change appreciably between seasons. Most dietary replacements occur at the same trophic levels. In fact, the entire trophic structure does not change much between seasons, although the overall system activity during the dry season falls by some 25 percent. Relatively little carbon recycling takes place in the cypress ecosystems, even by comparison with physically more open

systems, such as the Chesapeake estuary. What recycling does occur, however, is exceedingly complex. In particular, the predation on eggs and juveniles of higher trophic elements by lower trophic level species complicates the cycling structure enormously and provides tens of millions of new pathways for recycle. Such “ovi-predation” has been neglected in most trophic budgets, but it could be of enormous significance in forecasting the results of system impacts.

The Florida Bay ecosystem: A 125-component budget of the carbon exchanges occurring during the wet and dry seasons in Florida Bay has been assembled. These trophic networks are the most highly resolved and complete foodweb ever to have been assembled for any ecosystem. As is the case with such detailed, quantitative descriptions of ecosystems, the overall configuration of trophic transfers yields numerous clues as to how the ecosystem is functioning. An analysis of indirect contributions reveals, for example, that seagrasses are the ultimate source of carbon for the system during the wet season. However, epiphytic periphyton becomes the foundation that sustains system activity during the dry season. These primary producers fuel ecosystem activity mostly via indirect routes involving passage through detrital links. There is some 37 percent more trophic activity during the wet season, as compared with the dry interval that follows. Nevertheless, more species appear to feed higher on the trophic ladder during the dry season than they do during the wet period. The taxon feeding highest on the trophic ladder is the raptors, which, on the average, feed at level 4.6. Such averages hide the existence of some very long trophic feeding chains, which in a few instances reach 15 transfers in length. Such long concatenations, however, move only an insignificant amount of carbon along their whole length. A remarkably high percentage of carbon is recycled by the Florida Bay ecosystem. Over 26 percent of total system activity involves recycling (a proportion exceeded only by coral reef ecosystems), and, quantitatively, most of these processes are carried out by the pelagic and benthic flagellates. The topology of the Florida Bay ecosystem is remarkably stable throughout the year.

A significant part of the funding for this research was provided from the U.S. Department of the Interior, South Florida Ecosystem Restoration Program “Critical Ecosystems Studies Initiative” (administered through the National Park Service) and from the U.S. Geological Survey, Florida Caribbean Science Center. Additional funding for the “Across Trophic Level System Simulation” was provided by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers.

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The Surficial Aquifer System in Southwest Florida

Bruce R. Wardlaw¹ and J. Luke Blair¹

Hydrologic models that simulate flow of ground and surface water will be used to predict consequences of many of the South Florida ecosystem restoration plans, as well as guide future land and water-management decisions. The U.S. Geological Survey is providing essential hydrogeologic data to extend existing and next generation water management, natural system, and other models across southern Florida to the natural boundary of the southwestern coast.

New data from several recently drilled core holes, which investigate the shallow surficial aquifer system in Collier and Monroe Counties, indicate that the aquifer is confined to sediments above a structural boundary formed by the top of the relatively untransmissive “unnamed formation.” The “unnamed formation” is a siliciclastic unit of Miocene and earliest Pliocene age that is roughly equivalent to the Long Key Formation below the Florida Keys. The formation consists largely of muddy sand with beds of mud and clay and thin isolated “clean” sands. The “clean” sands may be transmissive, but the unit as a whole can be considered to be untransmissive.

The top of the “unnamed formation” forms an irregular structural horizon that can be used to predict the depth of the transmissive beds and flow direction. The irregular surface forms a ridge of shallow depths paralleling the southwestern coast, deepening away from this ridge both to the northeast and southwest. Northeast of this ridge, toward the central part of South Florida, water flow is confined to sediments lying immediately above the “unnamed formation,” and because this surface slopes, water flow direction can be predicted. The flow would be away from the structurally high ridge and then toward the southeast along the structural trough near the central part of South Florida. These new data will greatly aid current modeling of ground-water flow for restoration and development decisions.

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Plant Communities of the Everglades: A History of the Last Two Millennia

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The history of vegetation, hydroperiod, and salinity at 20 sites in the historic Everglades was reconstructed in order to understand the natural variability of the system and its response to past environmental changes. These sites are located in marshes and sloughs of the predrainage Ridge and Slough area, Taylor Slough, elongate tree islands in Water Conservation Area 3 (WCA-3), and the mangrove fringe along Florida Bay. Using the palynological record from these sites, we documented regional changes in hydroperiod and vegetational composition during the intervals known as the Medieval Warm Period (9th-14th centuries) and Little Ice Age (15th-19th centuries) as well as the changes on a more local scale in response to the 20th century alteration of the ecosystem.

Sediment cores collected in WCA-1, 2A, 3A, and 3B document the history of Ridge and Slough sites over the last 2,000 years. From about A.D. 0-800, each site was analogous to a modern slough, with abundant floating aquatic vegetation (such as *Nymphaea* and *Utricularia*), long hydroperiods, and relatively deep water. From about A.D. 800 to 1200, pollen of weedy annual plants (such as *Amaranthus* and the *Asteraceae*) dominated assemblages, indicating greater fluctuations of hydroperiod and water level, more frequent droughts, and/or greater fire frequency. After a return to wetter conditions and slough vegetation in the 13th and 14th centuries, most sites exhibited greater abundance of trees and shrubs, suggestive of drier conditions, during much of the 15th through 19th centuries. During the 20th century, all sites have undergone further shortening of hydroperiod; some also show responses to localized events, such as nutrient enrichment or construction. These changes are of a greater magnitude than those that occurred naturally.

Two tree islands in WCA-3B have been analyzed to determine their age and development and to understand controls on development of elongated, fixed tree islands. Analyses of cores from the island head, tail, and surrounding marsh indicate that conditions on the present tree islands were drier than the surrounding marsh as long ago as 4,000 yrBP. Cores from the present islands indicate that moderate-hydroperiod marshes with frequent fluctuation of hydrologic conditions occupied the sites while the surrounding region was covered by long-hydroperiod sloughs. Further field work will help establish whether this apparent hydrologic difference results from paleotopographic differences or differential permeability in the underlying limestone, or from some other factor. The initial phase of tree-island development consisted of shortening of hydroperiod, increased abundance of fern spores, first appearance of tree-island taxa (such as *Salix*, *Cephalanthus*, and tropical hardwoods), and elevation of phosphorus levels. Mature tree-island vegetation is represented in the pollen record by dominance of fern spores, and phosphorus levels are extremely high. The tree islands themselves are old features, with initial tree-island formation beginning at about 3,200 yrBP on Gumbo Limbo Island and 1,800 yrBP on Nuthouse Island. On the present island heads, the existence of moderate hydroperiod marshes, common fish bones, and high phosphorus levels prior to development of the tree islands suggests that the sites may have served as base colonies for wading birds prior to development of the tree islands. This information should be helpful in developing plans to artificially create tree islands at other sites in the Everglades.

Sites in the mangrove fringe along Florida Bay provide a long-term record of vegetation and salinity change. In the southernmost site, a change from freshwater to brackish conditions occurred about 700 yrBP. At that time, freshwater marshes were replaced by brackish marshes, and brackish species of foraminifers and molluscs were added to the previous suite of terrestrial and freshwater molluscs. Dwarf-mangrove assemblages became established there by the 17th century, with progressively later establishment in northern sites. During the 20th century, the replacement of brackish marshes by mangroves appears to have accelerated; the timing of this change coincides with a period of increased salinity fluctuation in Florida Bay and decreased freshwater flow from the Everglades.

These long-term records illustrate the natural variability of the system in response to climatic events during the last two millennia. Hydroperiod fluctuations are recorded at all sites, with relatively dry conditions occurring around 1,000 yrBP and during the last century. Disruption of hydroperiod during the 20th century has resulted in both shortening and altered seasonality of hydroperiod, affecting both the terrestrial Everglades system and the marine system in Florida Bay. Localized responses of vegetation to disturbance or nutrient enrichment provide useful measures of the response time of the system to changes and of the level of change that the system can tolerate. Such data are critical for prediction of future responses of the ecosystem to changes in environmental management.

This research has received critical support both in logistics and planning from a number of cooperating agencies, including South Florida Water Management District, Florida Game and Fresh Water Fish Commission, Florida Geological Survey, U.S. Army Corps of Engineers, Big Cypress National Preserve, Everglades National Park, and Loxahatchee National Wildlife Refuge.

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Wading Bird Simulation Modeling and Integration into ATLSS Landscape and Fish Models

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The wading bird model is part of the package of the “Across Trophic Level System Simulation” (ATLSS) models. Its focus is to investigate the dynamics of colonies and nesting success in relation to different hydrologic scenarios and the resulting spatial and temporal distribution of their prey. The model uses an individual-based approach and simulates the activities of potential nesting adults for a period of time immediately preceding the formation of a nesting colony and then through the entire nesting season. In an individual-based model each of the adult birds, as well as each of their offspring, are modeled as individuals. The University of Tennessee landscape fish model provides prey for the simulated wading birds and has been linked to the wading bird model of Wilfried Wolff by an interface developed by Paul Fishwick.

The individual wading bird in the model is described by a set of species-specific rules that govern its behavioral activities. A model wading bird does not operate on a fixed time scale, because its behavioral activities are of different durations. Instead, the wading bird model uses an event-driven approach, in which each bird sets its own time scales depending on its current activities. In its current version, the wading bird model operates on spatial grid of 500 x 500 meter grid cells.

Decisions made by the birds are guided by various constraints. Each bird must meet its energy demand during each day. If it cannot meet this requirement, the bird is assumed to have died or left the system and is removed from the simulation. Colony formation, courtship, nesting, and egg laying are also determined by energetic constraints. The model assumes that nesting will only start if females have acquired sufficient energy reserves to produce eggs. Unless female birds can meet these demands, nesting will not start. Colony formation and nesting is, therefore, directly tied to the availability of prey and the ability of the birds to obtain enough food in close proximity to their potential colony site.

Examples of activities on shorter time scales are when and where to forage. Feeding sites chosen by an individual bird are based on partial information about the system. The model assumes that each wading bird has some knowledge, perhaps obtained from visual cues when flying or soaring, concerning the water depth of various locations (that is, cells in the model) in its foraging area. A wading bird, however, does not know the prey availability at a given site before landing and having foraged there. The wading bird can select a cell in the appropriate water-depth range, but randomly otherwise, and search for food in that cell. Otherwise, it can choose to join one of the flocks of wading birds from its own or from a different colony that may already be feeding. This latter behavior mimics gregarious foraging, typical of wading birds.

Larger feeding aggregations are assumed to be attractive to searching birds than smaller ones or even single birds. Because wading birds leave their feeding site if their foraging success is low, such rules ensure that feeding aggregations can form quickly and grow in size. On the other hand, large aggregations of foraging wading birds can rapidly deplete their prey. Though each capture of prey by a bird is a stochastic event, the rate of prey captures depends on the current fish density in the cell the bird is foraging in. If its foraging success decreases, a wading bird will leave its current feeding site and search somewhere else. Large feeding aggregations will therefore break up as soon as prey has been depleted and it becomes unprofitable for the wading birds to forage there.

All activities have a specific energetic cost. Foraging itself is relatively inexpensive, while searching and flying across the landscape requires more energy. Flight energy is determined by the weight of the bird, the type of flight and the distance the bird has to fly. Wood storks, for example,

predominantly choose soaring flight for larger distances and may not leave the colony unless they can do so, whereas white ibis mostly use flapping flight which is less efficient and has a higher energetic cost. At the end of each day, the energetic costs of all activities of a bird during the day are tallied. If food intake was insufficient to meet these costs, the energetic reserves of the bird such as fat deposits are decreased. Similarly, any surplus food intake increases the energy reserves of the individual bird.

Nestlings are also modeled as individuals. Simulating nestlings, however, is much simpler because their main activity consists of eating the food brought back by their parents, and sleeping. Because the main interest of the model is to determine whether or not a nestling receives enough food to fledge successfully, it suffices to keep track only of their food intake. To model the growth of the nestlings, their relative sizes are assumed to be solely determined by their individual total cumulative food intake. Total food intake, therefore, determines whether the nestlings have grown to a size enabling them to leave the nest and forage on their own.

Nestlings are fed by regurgitation. Adults begin feeding their young soon after hatching. As a result of asynchronous hatching and differential feeding, siblings differ in size and vigor. In general, competition for food among wading bird nestlings is fierce and larger nestlings are therefore assumed to receive more food than their smaller siblings. Such rules ensure that brood reduction as well as siblicide occur in the wading bird model for species that are known to show this type of behavior. If the parents cannot find enough food to meet their own energetic demands, they will desert their nest and the nestlings will perish.

From experimental measurements, it is known that a wading bird nestling must attain some threshold level of accumulated food in order to fledge. If the nestling does not receive this amount of food before the rainy season begins, it will usually die because the parents will no longer be able to provide food sufficient for its survival. Similarly, parents will gradually cease feeding nestlings after a certain amount of time, after which the nestlings have to leave the nest and fend for themselves.

The model keeps track of colony sizes and the number of nesting adults as well as the number of successfully fledged nestlings after the breeding season is over. Because energetic constraints drive most of their activities, in particular the onset and timing of nesting, different environmental conditions will lead to varying reproductive behavior and recruitment of young wading birds into the population.

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